Best Management Practices for Non-Chemical Weed Control

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Contents

Introduction

Stewardship to protect and restore natural lands across California relies on the effective control of invasive species. Invasive plants are plant species introduced into the state that have spread extensively and are now causing environmental and economic damage. They represent only a small percentage of the many species that have been purposefully or inadvertently introduced to California, but they do a disproportionate amount of harm. Working to control them is essential to stopping their spread and reducing their impact.

For generations, land managers, volunteer land stewards, avid home gardeners, and agriculturalists have been learning techniques from one another to control different kinds of weeds effectively and efficiently in different environments. (Invasive plants are considered weeds — unwanted plants — and we use the terms interchangeably here.) The audience for this report is land management practitioners stewarding wildland habitats (both professional and volunteer), and the focus is on Best Management Practices (BMPs) for employing these techniques for controlling weeds.

There are many ways to control invasive plants. Effective invasive plant control often requires combining multiple tools and techniques to address all life stages and includes prevention practices to stop further introductions and spread. This is called Integrated Pest Management, or IPM, and is focused ultimately on ecosystem heath. The BMPs in this guide provide information on a range of approaches that can be used alone or in combination to control weeds. These BMPs are part of a larger collaborative project by the California Invasive Plant Council in collaboration with University of California's Division of Agriculture and Natural Resources (UC ANR) with funding from the California Department of Pesticide Regulation. In addition to compiling these BMPs, the project will build an online decision support tool to help land management practitioners assess and choose non-chemical weed control approaches for their specific real-world situations.

Practitoners, policy makers, and the public are concerned about the consequences of pesticide applications, including herbicides. While herbicides are an important tool in the IPM toolbox, interest has grown in understanding what can be accomplished without using herbicides, using non-chemical methods only. This set of BMPs covers that ground. Though many of the techniques described here are often used in combination with herbicides for maximum efficacy, the focus here is on using non-chemical methods exclusively.

The information presented here is based on contributions from practitioners across the state. This expert knowledge is invaluable, though certainly incomplete as well. The field continues to evolve, and while there is a deep literature on weed control, much of the applicable information still comes from the collective experience of fellow land managers.

The information in this guide is organized into sections based on similarities in the certain techniques — either how they are applied or how they control a weed. We cover:

- Removing whole plants — this includes various methods all designed to help remove an entire plant, or as much of it that you can get to, from the ground.
- Controlling plants by cutting — there are many ways to sever plant stems, from sawing down a tree to mowing grass with a string cutter, and these can be used to suppress weed growth or to fully control weeds by exhausting their energy stores (typically with repeated cutting).
- Controlling plants in place — some treatment approaches can damage weeds effectively without removing them. Flaming and steaming do this by applying heat, and girdling does it by cutting off the circulation of phloem in a woody plant.

- Covering plants with sheet barriers — whether using tarps or mulch, placing a physical barrier on the ground can stop weed growth. Using clear tarping to trap heat can solarize weeds.
- Controlling plants at the community scale — there are a family of techniques that work at the scale of the entire vegetation community, including burning, grazing, competitive planting, and soil cultivation (such as plowing).
- Biological controls — finally, there is the research, permitting and release of insects or pathogens from the home range of a particular weed species that will damage it without harming other plants.

These techniques provide a wide range of options for the land manager to choose from, depending on the weed to be controlled, the site to be worked on, and the particular circumstances of the effort. While the list of techniques covered is not exhaustive, it does represent those non-chemical approaches considered most effective by practitioners. BMPs focus on weed 'control' in which the land manager aims to fully remove the weed's impact from an area. Some techniques can also be used for weed 'suppression,' in which the goal is to reduce the cover of weed and thus partially reduce its impact.

The BMP for each technique includes an overview, a general 'how to' section, a description of combining with other techniques, conditions under which it is especially effective (and ineffective), and a rating of relative risks to tool operators and natural and cultural resources. General risks associated with the outdoors, such as heat exhaustion, sun burn, poison oak, biting/stinging insects, snakes, etc., are not specifically called out; practitioners should be aware of proper safety protocol and personal protective equipment (PPE).

An online decision support tool that organizes non-chemical techniques by their efficacy for specific plant and site characterists is available at weedcut.ipm.ucanr.edu/

The collected expertise in this guide provides a foundation for land managers and others to understand the strengths and weaknesses of different approaches, with the goal of implementing effective stewardship programs. In the spirit of continuing to grow this type of information base, we encourage land managers to take opportunities to share their experiences and learn from each other.

Key References for Weed Control in California

Specific references are listed for each BMP. Several more general references bear listing here as overarching resources for these approaches:

- The Cal-IPC website (www.cal-ipc.org) contains links to:
  - Assessments and management notes for 200 invasive species.
  - A downloadable version of the *Weed Workers' Handbook*.
  - Training videos, including *Principles of Weed Control*, *Techniques for Controlling Woody Plants*, *Overview of Manual Weed Management Tools*, and *Tool Belts*, including excellent practical insight from Ken Moore, a wildland weed warrior icon in California.
- The Weed Research & Information Center at U.C. Davis (wric.ucdavis.edu/) compiles research on control approaches for individual weed species. They produced the reference manual *Weed Control in Natural Areas in the Western United States*, a comprehensive manual by California's premier weed scientist, Dr. Joe DiTomaso, and co-authors that compiles recommended non-chemical and chemical control methods for 340 weeds.
- *Invasive Plants of California's Wildlands,* a guide to the state's worst weeds, along with tips on how to remove them by Dr. Carla Bossard and co-authors.

1.Removing Whole Plants

Removing whole plants encompasses a wide variety of tools and techniques that are designed to remove entire plants, roots and all when possible, so that they cannot regrow and reproduce. This section includes the following BMPs:

- Manual Removal (whole plant removal with hand tools).
- Grubbing with Hoes.
- Scuffle Hoeing.
- Severing Roots.
- Whole Plant Temoval with Large Equipment.

1.1 Manual Removal

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Overview

Manual removal of weeds by hand or using hand tools (hereafter referred to as manual removal) is one of the most common techniques used across the state. The goal of this technique is to remove entire plants, including their roots, to the point where they cannot resprout. Manual removal is not recommended for species that can regenerate from vegetative structures left behind underground. Weed species that reproduce only by seed are generally easier to control with manual removal than are weed species that can reproduce vegetatively.

Weeds are removed by pulling or digging up the plant from the soil. Using a tool often provides a better grip on the plant or provides a fulcrum to leverage the plant and roots out of the soil. This technique is used by both volunteers and professionals and is often the best non-chemical method to eliminate nascent weed populations as they are discovered. Manual removal can be very time- and labor-intensive and therefore more costly compared to other techniques, especially in the absence of volunteer labor.

Lightweight, low-tech tools needed for using this approach on small plants can be carried to remote areas without road access or areas that are too steep for livestock grazing, though steeper areas require more experienced workers for safety reasons. Larger, heavier tools, like weed wrenches, are needed for larger plants. Examples of tools commonly employed in manual removal include:

- Your hand.
- Dandelion/forked weeder.
- Digging bar.
- Garden fork/spading fork.
- Hori-hori soil knife.
- Lineman's pliers.
- Mattock/Pulaski/pickaxe.
- Shovel/trenching shovel/sharpshooter shovel.
- Weed wrench.
- Chain and winch.

Which tool you select can make a big difference in how successfully you can control a species. There are many tools to choose from. Beyond just using your hand to pull a plant, a few of the most popular are described below.

A dandelion or forked weeder is a popular weeding tool for smaller, herbaceous (non-woody) species with a tap root in loose soil. It is inserted into the soil and used to pry out the taproot (it is less useful for plants with fibrous or spreading roots). A hori-hori soil knife is also very helpful for removing smaller

plants without breaking them at their base. This tool can be used to dig out smaller weeds or to sever the shoot from the root (see Severing Roots BMP). A garden or spading fork can be used to remove plants with fibrous root systems such as bunchgrasses, or even shrubs with limited, shallow root balls (like planted ornamentals) and works best with loose or moist soil. Lineman's pliers are often used by field workers to provide extra grip for pulling plants with sturdy stalks in drier soils (e.g., removing individual bolting starthistle or knapweed plants).

Shovels, trenching shovels, and sharpshooter shovels are some of the most commonly used hand tools for manual removal of larger plants and shrubs. They are especially useful in providing extra cutting and prying power needed to remove perennials with more developed roots under loose or moist soil conditions. A digging bar can be used to remove plants from cobbly or rocky soils where shovels or lighter-duty tools cannot penetrate the soil surface. These bars can be shortened in a machine shop to reduce weight for controlling populations that required extended hiking to access. The long form is a heavy-duty tool that provides more leverage but can more easily injure the user or other workers if proper attention to the tool and surroundings are not observed. A mattock, pickaxe, or Pulaski can be used to pry out larger perennial bunchgrasses like fountaingrass, pampas grass, or jubata grass, or large perennial herbaceous species like fennel. These tools are most effective for removing species with shallow root systems in drier soils but can also take out some more deeply rooted plants.

The weed wrench is useful for uprooting shrubs or small trees like broom species and privet. It works best when a main stem is accessible at ground level. Larger woody weeds can often be pulled from the ground (especially in moist soil) using a chain that is securely wrapped around the main stem and attached to a hand-winch that is secured to a much larger tree nearby. Caution should be taken by standing clear to a distance greater than the length of the chain in case it breaks as pressure is applied.

How to Use

Manual removal can be effective for annuals, biennials, and perennials and works best under moist soil conditions. This section will not provide exact prescriptions for how to use tools but will provide guidance on how to select tools for specific environments and types of plants. Timing of manual removal is key and should occur before seed set and, most importantly, seed release.

Annual forbs can be pulled by hand or with hand tools, though many herbaceous species with fleshy stems (e.g., sowthistle) are prone to breaking off when being pulled, resulting in incomplete removal. Make sure to grab plants at their base when pulling and to assist with a digging tool if a plant is prone to breaking off. For fibrous-stemmed plants, try using lineman's pliers to improve your grip. Annual grasses can be removed when young with a garden fork or, more efficiently, by hoeing (see Scuffle Hoeing BMP).

Perennial bunchgrasses can be removed effectively with a pickaxe, mattock, or Pulaski if care is taken to remove all tillers. This technique is counterproductive for sod-forming species when sod cannot be entirely removed.

Perennial shrubs, trees, and vines are more difficult to remove as whole plants and should be targeted as young plants or seedlings. Weed wrenches can be used for older, woody plants. Clear obstructions away from the base of the plant in order to securely fasten the jaws to the main stem at ground level

and provide room for pulling back on the tool. Older perennials have more developed root systems that can resprout if not completely removed. Vines should not be removed by digging or pulling unless all roots and stem pieces can be removed.

Seed bank longevity of target species does not generally affect success of this technique if control efforts are maintained consistently over multiple, consecutive years. In California, weeds that germinate in the winter can be more challenging to remove selectively than those that germinate in the warm season because the majority of native species also germinate in the cooler fall, winter, and spring months, making selective removal more difficult. Neither seed production nor flowering season have much of an effect on how well manual removal works, but a prolonged flowering period will mean that more effort will be required to achieve effective control through multiple rounds of removal.

Manual removal becomes dramatically less practical as the patch size to control becomes larger. This can be somewhat mitigated by having a large labor force and multiple, consecutive years of consistent control.

Manual removal can be very effective for weed populations that are a considerable distance from roads, but this also assumes smaller areas of infestation due to logistical constraints of travel and transportation of tools, water, and safety gear for workers. Weed populations in steeper terrain are not well-suited for this technique due to erosion concerns created by forcibly removing roots. Worker safety is also a concern in this scenario, though in certain cases small or scattered populations can be targeted if safe access is available.

Smooth and cobbly soils generally do not impede manual tool removal, but rocky soils can sometimes prevent complete removal of underground structures. Weeds can be easier to remove in muddy soils, but access may be more difficult and damage to habitat may be an issue. Plants may also readily re-root if left on the surface of muddy soils. This is also true for marsh and wetland habitats where muddy soils are common.

Density of a targeted invasive plant should not impact effectiveness of manual removal, but higher target plant densities will require more intensive control efforts as individuals are less likely to be detected by workers. For native plant cover, there is a trade off with higher cover providing more potential to outcompete weeds following control, while also increasing the chance of non-target damage and reducing detectability of target plants.

Special Tips

Fill in holes created by manual removal both to minimize regrowth of root fragments left behind from incomplete removal and to mitigate soil disturbance.

If plants are pulled at flowering and during seed set, seeds may still be viable. Collect and transport (or mulch in sealed bags on site) any plant material that may contain mature seed. If material is being transported from a site, use heavy duty garbage bags to avoid spreading seed along access routes. In backcountry areas where removal of materials is impractical, plants can be stacked in pyramids with roots upward to ensure that roots dry out. It may also make it easier to relocate previously treated areas for follow-up work in the future.

When using a weed wrench to remove a large woody plant from moist soil, place a flat piece of metal or strong wood under the fulcrum to keep it from sinking into the soil. A saw may be useful for removing the upper part of the plant to access the main stem for removing the roots. Be sure to leave sufficient stem for grabbing with the weed wrench and your hands, generally two feet.

A leaf or garden rake can be used to collect large seeds (e.g., from goatgrass) or grass thatch (e.g., from bromes or medusahead) for disposal. Raking with a fixed-tooth rake can be used to remove pieces of sprawling or vining weeds like English ivy.

Optimal Conditions for Use

Optimal conditions for manual control techniques include a well-trained and consistent labor source, easy site access, moist soils, flat to moderate slopes, small target populations, weed species that are annual or biennial or young perennials with less-developed root systems, species that cannot resprout from vegetative fragments, and species that have gone to seed. Manual removal can be especially useful when fine-scale selectivity is required due to the presence of cultural artifacts or rare species of plants or animals.

Caveats

Do not use manual removal methods for any species that is a prolific resprouter from underground structures (e.g., Japanese knotweed) unless that species can be entirely removed both aboveground and belowground from a site. Attempts at manual removal can make the problem worse. Disturbance from digging can also flush the existing seedbank of a weed, which is a detriment if left untreated but can also be used as a strategy for certain species to remove future generations of plants.

Potential Hazards to Humans, Environment, and Cultural Resources

Human hazards. Low-moderate risk. There is an inherent risk of human injury in using hand tools due to potential injury from heavy or sharp tools and the presence of large numbers of potentially inexperienced workers. Risks can be exacerbated when working in certain locations, such as roadsides where vehicle hazards are present, and rough terrain or extended hikes where the potential for injury during foot travel is increased. Repetitive stress injury and back strain is also possible from extended use of hand tools.

Cultural resources. Low-moderate risk. Work can be sited accurately to avoid known cultural artifacts. However, soil disturbance associated with manual removal, especially when tools are employed, still has potential to damage sensitive cultural resources.

Habitat. Low-moderate risk. In thick cover with limited visibility of the soil surface, there is a higher risk of damage to non-target plant and animal species. Also, the risk that weed workers can track or move weed seeds and soil pathogens on clothing, tools, and boots is higher than for some other techniques due to the close physical interaction with target plants. Larger crew sizes associated with manual removal activities increase risk.

Sensitive species. Low-moderate risk. Take note of and avoid nesting animal species and sensitive plant species.

Erosion. Low-moderate risk. If soil is disturbed by plant removal, then there is a risk of erosion. Erosion risk is higher on steeper slopes. Fill in holes left from root removal and cover exposed soil surfaces with litter or other plant material to minimize erosion. Level of erosion is directly correlated with density of the target population being removed.

Other Non-Chemical Methods to Combine With

Manual removal can be combined with any other weed control technique. The flush of weed seed emergence following soil disturbance associated with this technique may be particularly well suited to control with methods that are effective and efficient at killing seedlings, thereby killing two generations of weeds in a single season. Manual removal can also be useful following large-scale activities or less selective techniques like mowing or broadcast herbicide application to remove late emerging individuals and resprouts.

Large pampas grass and jubata grass plants can be successfully removed by using a combination of manual removal and other cutting tools. First cut grass down to a low height with a brush cutter. Then cut a grid pattern vertically into the base of the plant through the root mass in the soil with either a chainsaw, reciprocating saw (see Cutting with Chainsaws BMP), or Pulaski, creating manageably-sized grid cells. Finally, use a mattock to pry out individual grid squares of grass. Flip so that roots are facing up to dry roots and eliminate re-establishment.

When Not to Use

Manual removal should not be employed on large weed populations where control is unsustainable or on species with extensive root systems or underground vegetative reproductive structures. It should not be used on plants that are already dispersing seeds unless seeds can be contained or unless there is already a large soil seed bank.

Photographs

Common tools used for whole plant removal of smaller weeds. Left: Hand trowel and forked weeder. Right: Soil knife or hori-hori. Photo credit, both images: Jutta Burger.

Two modifications of common digging tools. Left: A forked weeder on a pole to improve weeding ergonomics Photo credit: Jutta Burger. Right: A digging bar shortened and sharpened to serve as a handy weeder. Photo credit: Marla Knight.

Whole plant removal sequence for mature artichoke thistle using a pickaxe. Note massive root structure and large hole that was dug to excavate the root. This technique is not recommended for undisturbed habitat because of the degree of disturbance that it causes. Photo credit: Dave Wilson.

Set-up for late season removal of crimson fountain grass with pickaxe (well-suited tool for rocky conditions). Note trash bin for plant material to safely dispose of seeds. Photo credit: Dave Wilson.

Manual removal tools for shrubs. Left: Sharpshooter shovel. Photo credit: Dana Morawitz. Right top: Close-up of weed wrench used for Scotch broom. Photo credit: William Welch. Right bottom: Demonstration of proper technique for using weed wrench. Photo credit: Stock images.

Demonstration of how to cut a jubata or pampas grass and remove it in wedges with a Pulaski. Photo Credit: Ken Moore (video still).

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1.2 Grubbing with Hoes

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Overview

Hoes are hand tools that have been used in agriculture for at least 4,000 years. As they have been in use for thousands of years and across numerous agricultural civilizations, a variety of hoe blades, handle types, and names for the tool have been developed. In general, a modern hoe consists of a wooden handle generally 4-6 feet long, and a wide flat metal blade that is perpendicular to the shaft. Usually, the blade is rectangular in shape, although many different blade shapes have been developed, from triangular, to more rounded and heart-shaped, to long and thin, to ones where the blade has been divided into tines, like a fork hoe.

The grub hoe is the most commonly used hoe type for land managers. It is used to cut into the soil in order to cut weed roots below the soil surface. When pulling or lifting the shaft, it can also be used to turn over the soil around a weed, uplifting some of its roots. A grub hoe is operated by lifting the shaft and swinging the blade into the ground, so the blade penetrates the soil and severs weed roots or stems. Grub hoes are best used on herbaceous annual weeds with a single central root and small- to medium-sized annual grasses. They can also be used effectively on perennials that have limited resprouting ability or that can be severed below the root crown from which they resprout. This tool does not work well on large woody plants, but it can be used to chop through small woody plants and seedlings.

Grub hoes are most useful for low-density weed infestations or for early detection and rapid response (EDRR) situations. A land manager can work small- to medium-sized weed patches before tiring. Generally, only small areas, such as several thousand square feet, can be managed with a hoe in a reasonable time with one or a few people. Hoes should be used where some soil disturbance can be tolerated.

This technique is used by land managers and volunteer groups in a wide variety of habitats. Hoes are lightweight enough to be easily carried long distances to a worksite. Many varieties of hoe types exist, and a specialized hoe blade can be used for a specific job or habitat. Grub hoes are relatively inexpensive. Maintenance and upkeep are mostly limited to keeping the hoe blade sharp and ensuring the blade is secured to the shaft.

How to Use

The wide variety of blade types can alter the specific use and effectiveness of a hoe. This section will not cover all the dozens of different blade types. Note that most garden hoes available in residential garden and home improvement stores (also known as “draw hoes”) are primarily designed for creating furrows

in soft soil for planting seeds and are not sturdy enough for field work. The grub hoe tends to be heavier and much more robust than a draw hoe and can be used in difficult weeding situations.

The grub hoe (alternatively called chopping, digging, ring, eye, field, or peasant hoe) has a ring (or 'eye') or collar at the top of the blade where the shaft is directly connected to the blade. The shaft of the grub hoe sits above or on the blade, which is different from a draw hoe which has a curved connector between blade and shaft. The blade of a grub hoe tends to be much thicker and heavier than a draw hoe, and some grub hoes have a slight but distinctly curved blade. The blade should be kept sharp to better chop weeds, and a small pocket file can help keep the tool sharp in the field. A sturdy grub hoe will weigh 2-5 pounds to better penetrate the roots and soil.

The grub hoe is used to cut into the soil to chop a weed below ground level and, when pulling or lifting the shaft, to turn over the soil around the roots. The shaft of the grub hoe is lifted and swung into the ground, so the blade penetrates the soil and severs weed roots or stems. The next movement is to either pull the shaft inwards towards the body to dislodge roots and soil, or to lift the shaft vertically, to minimize soil disturbance. A grub hoe can also be used to scrape the soil surface to remove weed seedlings or sever stems. Because the hoe disturbs the soil, weed seeds near the surface may become buried after using the hoe which may contribute to soil seed bank. Though a hoe can be used to clear dense weed patches, it can also be used to carefully work around non-target species.

Often a grub hoe is best used to treat weeds with a single taproot as found in many dicots, such as goat's head (*Tribulus terrestris*), tumbleweed (*Salsola* spp.), smaller cheeseweed plants (*Malva parviflora*), and dandelion (*Taraxacum officinale*). It can also be used to treat invasive annual grasses such as bromes (*Bromus* spp.) and oats (*Avena* spp.). If a grub hoe has a rectangular head, the user can rotate the tool 30-45 degrees to use the pointed corner to cut larger tap roots, such as on larger cheeseweed plants. In addition, when held at an angle the corner can penetrate wet soils effectively, although this will wear out the corners and they will need to be sharpened sooner.

A grub hoe with a pointed, triangle-shaped blade is also useful in situations where more delicate and precise weeding is needed compared to a rectangular grub hoe. Sometimes this hoe is called a triangle hoe or pointed hoe. (Others use the name triangle hoe for a similar tool that has a triangle shaped blade but has a wrought iron neck more similar to a draw hoe and like a draw hoe may not be sturdy enough for most wildland uses.) The blade of a triangle-shaped grub hoe is, as the name suggests, shaped like a triangle, and swung like a standard grub hoe. The pointed tip is used to precisely weed around non-target plants, such as if annual weeds were growing near a native shrub seedling. The triangle grub hoe can also more easily penetrate a thick tap root, or soils that are soggy or compacted, than can a rectangular grub hoe. The shaft of a triangle grub hoe can be mounted to either the back of the blade forming a long triangle, which will penetrate the soil more deeply, or can be mounted in the middle of the triangle creating a tool with two working edges, one being the pointed tip and the other side being the back flat edge.

A grub hoe can also be used to treat plants with aboveground prostrate runners, such as ice plant (*Carpobrotus* spp.) or St. Augustine grass (*Stenotaphrum secundatum*). In this case the runners will need to be 'grubbed out' to chop large plants into smaller manageable patches. The user will need to ensure all of the plant parts are removed since small plant fragments can resprout and survive the hoeing treatment.

The hoe is easy to use on a variety of plant growth forms and habitat types. A hoe can be used any time of the year, as long as the soil can be worked. Hoeing may be most effective when flowers have developed but seeds have not yet matured on the plant. Treatments with a grub hoe will be more effective when weeds are smaller, and their roots are less developed. It will also require less energy to chop out a younger plant compared to an older plant. Weeds can be treated at nearly any time in development with a hoe. Perennials can be treated at any time but should be treated before or at the flowering stage to minimize seed set.

Under dry conditions or compact soils, more force needs to be applied to swing the blade deep into the hard, dry ground. In hard soils, a grub hoe with a narrow blade will penetrate the soil better than a wide blade, and a heavy-duty triangle hoe will be even more effective, but will dull more quickly.

A high-quality grub hoe costs less than $100. With proper care and sharpening, a hoe can be used for many years. The cost of the tool is cheap compared to the labor to use it, so a grub hoe is best used in treating small infestations or small areas. A person can only hoe a small fraction of a gross acre with moderate weed cover in a day. In agricultural settings, 10-25 people can hoe about 2.5 acres a day depending on the crop being grown. Density of weed cover, topography, and rockiness of soil will affect the speed of treatment. If weed cover is low, e.g., 1-5%, then a single person could manage a gross acre in a day, effectively hoeing only a few thousand square feet of weeds. The light weight of a hoe, compared to herbicides or mechanized tools, makes it a very useful tool in low-density weed infestations and in EDRR situations for non-resprouting annual weed species, where workers might hike long distances to a site. Similar benefits exist in terrain that is difficult to walk through, such as on slopes or unstable soils, where carrying a lightweight tool is safer and more efficient.

Special Tips

For better penetration in hard soils, use longer, skinnier hoe blades. A freshly sharpened blade will increase soil penetration and reduce user fatigue, so keep blades sharp by filing. Blades become dull more quickly when used in rocky or cobbly soils.

Under conditions where the soil is hard, a grub hoe can be used to sever weeds at ground level by scraping, although oscillating hoes are generally preferred for this (see Scuffle Hoeing BMP). In soils that are moist, loamy, or soft, a grub hoe may be used to pull out weeds by pulling the hoe across the soil surface.

Consider which of the many grub hoe designs may be most useful for your situation. Forked hoes are used more for dislodging weed roots in loose soils. Some hoes are designed for niche uses such as planting tree seedlings (i.e., a hoedad). A variety of hybrid tools are also available that combine a hoe blade with other tool heads. For instance, a mattock combines a pick and a hoe implement in its dual-purpose head.

Optimal Conditions for Use

The grub hoe is most effectively used for plants that crown sprout, are shallowly rooted, or are not too woody, in soils without rocks or cobbles, and in relatively flat terrain.

Caveats

In order for control with a hoe to be successful, all parts of the weed that can produce new plants must be severed from their roots. If the plant can resprout or form underground storage structures, such as nutlets, bulbs, or corms, hoeing plants may not be sufficient to control the population. If hoeing does not completely remove plants that can regrow from plant fragments, the technique may actually help to propagate rather than suppress a weed. Hoeing can disturb soils, creating areas where some weed species may thrive, including tumbleweed (*Salsola* spp.), mustards (*Brassica* spp)., and stinkwort (*Dittrichia graveolens*). Soil disturbance may also bury weed seeds, promoting future germination through a seed bank.

Potential Hazards to Humans, Environment, and Cultural Resources

Human hazards. Low. The most direct hazard from using a hoe is being struck with the blade or shaft. Workers should be well separated so they do not injure one another when swinging a hoe or striking the blade on the ground. Worker training is advised. A good rule of thumb is 10-foot spacing between workers ("watch your dime!"). Closed-toe shoes or boots may prevent or lessen injury if struck on the foot with a hoe. If used too aggressively, users may get blisters on their hands or may get fatigued quickly. Workers should use a hoe that allows them to stand upright without too much bending to lessen the strain on the back. Finding the right type of hoe blade, shaft length, balance of the hoe, and regular sharpening may alleviate these problems and improve ergonomics. Repeated stooping can cause significant back injury, especially with too short a handle or if the hoe is used improperly or not sized properly for the worker. The short-handled hoe has been banned from use in the professional contractor industry in California for worker-safety reasons.

Cultural resources. Moderate. A hoe can damage objects below ground so it should be used with caution in culturally sensitive areas.

Habitat. Moderate. Hoeing can disturb soil creating conditions where some weeds thrive, especially in high light environments. This tool can also disturb biological soil crusts in a wildland setting.

Sensitive species. Low-moderate. Hoeing may damage small animal burrows.

Erosion. Low-moderate. Since a hoe is relatively small and is manually powered, erosion would become a risk if a large group of people were intensively hoeing a single area, especially if the site was sloped, near a streambank that could erode, or on highly erodible soils.

Other Non-Chemical Methods to Combine With

Other hand tools that can remove woody weeds, such as weed pullers, saws, and cutting tools (see Controlling Plants by Cutting BMPs) are useful when working on sites that have a variety of weed types, such as annuals and woody or mature perennial weeds. On sites where precision work needs to be conducted, hand pulling or small hand tools may be needed around sensitive plants.

When Not to Use

If a weed is able to reproduce vegetatively, there is a significant chance the grub hoe will not be an effective tool and may even spread plant fragments around. This includes deeply rooted perennials like perennial pepperweed (*Lepidium latifolium*) and Japanese knotweed (*Fallopia japonica*). This also includes weeds that have underground storage structures, (rhizomes, nutlets, bulbs, or tubers) such as nutsedges (*Cyperus* spp.) and Johnsongrass (*Sorghum halepense*). And it includes weeds that form stolons or resprout from nodes, such as Bermuda grass (*Cynodon dactylon*) or Cape-ivy (*Delairea odorata*), since the chopping action of the hoe can sever runners and numerous plant fragments may re-root in the soil.

Photographs

From left to right: a 10-inch-wide swan-neck garden hoe (aka draw hoe), an 8-inch-wide grub hoe, a 5.5-inch-wide field-style grub hoe, and a 5-inch-wide triangle-shaped grub hoe. (Note: The swan-neck garden hoe is not recommended for wildland weed use and is shown for comparison purposes). Photo credit: Christopher McDonald.

This 8-inch-wide grub hoe, also called a grape hoe, has a curved blade. Photo credit: Christopher McDonald.

A grub hoe can be swung forcefully with the blade perpendicular to the surface to dig out deeply rooted weeds. Here, an 8-inch-wide grub hoe is being used to sever prickly lettuce (*Lactuca serriola*) below ground level. Photo credit: Christopher McDonald.

A grub hoe can also be angled to sever the weed at the soil surface. Here, the hoe is being used to sever prickly lettuce (*Lactuca serriola*) at the surface. Photo credit: Jack McDonald.

A triangle-shaped grub hoe, with a blade tapering from 5 inches at the widest to 1.25 inches wide at the tip. Photo: Christopher McDonald.

Triangle-shaped grub hoe being used to precision-weed near a small native Lupine (*Lupinus truncatus*) (bottom center). Photo credit: Natalie McDonald.

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Supplementary Information

Small patches of weeds can be easily and effectively controlled with a grub hoe with few regards to the density of the weed population. It becomes more difficult to hoe large areas. As weed cover increases, it becomes somewhat more difficult to treat every single weed in the population. Often, two or more hoeing treatments are needed to catch those weeds that survived the first treatment because they may have been accidentally buried or missed.

A grub hoe can be very effective on small- to medium-sized grasses, but large perennial bunch grasses may not be an appropriate target. As shrub size and woodiness of the stem and roots increase, the tool becomes ineffective. Many weedy vines are able to re-sprout from a treatment, including from plant fragments in moist soils. In those cases, a grub hoe would be ineffective. Seedlings of all plant growth forms including shrubs, trees, and vines can be easily treated with a grub hoe.

As long as the plant being targeted with the hoe does not re-sprout, hoeing will be effective. Many perennials can resprout when cut, even a few inches below the soil surface and hoeing treatments will not be effective. Hoeing can be a successful technique on smaller woody perennials, but it is not applicable when the stem is too woody to cut and a cutting tool would be needed (such as an ax, saw, or loppers).

When used correctly and on susceptible weeds, the grub hoe is a highly effective tool regardless of propagule production. Because the blade is relatively small, nearly every plant will need to be treated to stop reproduction. With plants that have a high propagule production, if a few plants are missed numerous seedlings may germinate next season, increasing the time it will take to eliminate the population. A grub hoe could exacerbate infestations of species that readily root from plant fragments (e.g., Cape-ivy) and should not be used.

Hoeing will kill the aboveground parts of a plant regardless of a species' seed longevity. This tool also disturbs the soil, which may cause some seeds to be buried, benefitting those weeds with moderate and long-lived seeds, perhaps germinating after treatments have ended years later. If treatments are repeated each year and plants do not produce new seed, then this method can be used to control weeds with moderate to long-lived seeds. If plants are difficult to detect, then this method will not work well on plants with long-lived seeds as treatments may not reduce the number of seeds being produced each year.

This technique is best suited to small scale infestations and is not suited for managing medium and large-scale infestations. As scale becomes larger, it is difficult to hoe that area unless labor is increased to levels appropriate to the infestation. Hoeing large areas is sometimes conducted by large groups of volunteers or workers as the tool is relatively easy to use, requires only moderate training and can be used for several hours by healthy volunteers.

When using a hoe on loose or difficult terrain, it can become difficult to properly swing a grub hoe without losing balance or risking injury. On the other hand, a long-handled grub hoe can reach weeds that are up or down a short incline where other shorter tools could not reach.

A hoe is somewhat less effective in habitats where water is present due to the fact that severed weeds may be able to re-root and continue growing. This can be mitigated by moving the cut weeds out of wet areas to places where they can dry out and desiccate. While a grub hoe can easily penetrate muddy soils, often muddy habitats can have weed species that resprout from below ground. In that case, this tool would be ineffective.

1.3 Scuffle Hoeing

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Overview

Scuffle hoes are designed to remove weeds by a push-pull ("scuffling") motion that cuts just under the soil surface. There are two types of scuffle hoes, the stirrup hoe and flat-bladed hoes, which include "dutch" push hoes and triangle hoes. Here, we will focus mostly on describing the stirrup hoe, which is generally more popular as a weeding tool with practitioners.

The stirrup hoe is also called an oscillating hoe, a scuffle hoe, a hoop hoe, or a swivel hoe. One common brand is the Hula Hoe™. It consists of a handle, generally about 5 feet long, with a blade in the form of a trapezoidal ring of sharpened metal shaped like a stirrup. The stirrup-shaped cutting piece is pulled along the surface of the soil or just under the surface of the soil to sever a plant stem or roots. The stirrup hoe can be worked with a forward pushing action as well as a backward pulling action, and often it is worked continuously back and forth in both directions. The metal blade may swivel a short distance in its frame such that it oscillates when being worked back and forth. However, in some models the stirrup shaped blade is fixed and does not oscillate. The stirrup hoe is not lifted and swung into the ground like the action of a grub hoe (see Grubbing with Hoes BMP).

Scuffle hoes work by cutting the root crown or roots of a weed depending on the depth of the cut. As long as the upper parts of the plant do not re-root into the soil and the underground plant parts do not produce new plants, then this method can be highly effective. It is not very effective on species that grow from underground storage structures, such as bulbs, rhizomes, or tubers, or plants that are woody or re-sprout from nodes or plant fragments.

Weeds should be hoed with a scuffle hoe when they are small- to medium-sized. A stirrup hoe in particular is a good tool to use when small- to medium-sized patches of weeds grow in low densities where workers might spend long periods walking to each patch. This tool is particularly effective on dense flushes of seedlings, especially from the late fall through mid-spring. Hoes are more efficient than hand weeding in this situation. When plants are left to grow larger, they are more difficult to control as the stems and roots become tough to sever.

A site may need to be treated several times in a season by scuffle hoeing for several reasons. Occasionally, weeds will re-root into the soil and may not die, especially if it rains shortly after a treatment or in wet soils, such as in wetlands or riparian areas. In dense infestations, it may be difficult to treat every single individual, especially with small annuals (in this case a broad scale method would be more effective — see BMPs on Mowing, Mulching, Tarping, or Solarizing). In other cases, some species may not be cut deeply enough below the soil surface with a stirrup hoe and may resprout. If treated species can resprout, then multiple treatments will be needed. Scuffle hoeing can cause significant soil disturbance when worked and should be cautiously used near weed species that grow especially well in disturbed soils.

A stirrup hoe is a very inexpensive tool. Cheap ones can be purchased for less than $20. However, at the lowest prices, the quality of the tool is also low.

A limitation with scuffle hoes is the amount of labor needed to treat large areas. Although few studies have been conducted with scuffle hoes, it is assumed here that their efficiency is somewhat similar to a grub hoe. In agricultural settings, a team of 10 to 25 people are needed to treat about 2.5 infested acres with a grub hoe in a day. If weed cover is low, between 1 to 5% for example, and weeds are small- to medium-sized annuals, then a single person could manage an acre in a day, assuming detectability of the weeds is high, because they would only be treating a few thousand square feet of weeds in a day. The ability to treat large areas with hoes limits their usefulness in medium- to large-scale weed infestations.

How to Use

A scuffle hoe is pushed and pulled on or just below the soil surface (often ¼ to ½ inch deep), to sever weeds at the base of the stem or at the top of the roots. In a dense weed patch, the stirrup hoe is worked continuously forward and backward. The motion entails pushing and pulling the arms, keeping a straight back, and slightly moving sideways to clear the entire weed patch. A stirrup hoe can also be used to cut individual weeds by using one short pull stroke after placing the hoe over the weed. If the weeds do not easily resprout (such as in some annual thistles, mustards, and spurges) and have been treated before flowering, the aboveground parts of the plant can be left in place to desiccate and die.

Regular sharpening helps maintain optimal performance. Some hoe varieties need more sharpening than others, depending on the quality and shape of the metal. If the blade of a hoe becomes dull it will need to be sharpened. In many wildland situations, it needs to be sharpened regularly, especially in soils with small rocks. A hand file carried in the field can help with this task, where a grinder can be used in the shop.

Several different manufacturers make stirrup hoes with different weights and strengths. Stirrup hoes with thinner handles and smaller blades may not be durable enough for professional land managers or volunteer groups. Some stirrup hoes have a flat bottom to the stirrup, where others are more rounded. The more rounded design (sometimes called a hoop hoe) can penetrate the soil deeper and can only be used in soils that are easy to work. Some stirrup hoes will weigh several pounds, have a stout handle, and robust mounting hardware and blade. Well-built hoes can last several seasons of field use, even with rough use.

Some on-site training may be needed to use the tool efficiently, especially for those using the tool the first time. Some users misunderstand that the tool is pushed and pulled and not intended to be lifted and swung into the soil, like when using a grub or draw hoe. Despite this minimal amount of training needed, the tool is much more efficient at weeding compared to hand pulling and can be more efficient at removing small plants than a grub hoe, while a grub hoe is more efficient at large or more woody weeds.

With a little practice, a scuffle hoe can be used as a precision weeding tool. If the blade of the stirrup hoe is turned to a 30-45 degree angle the narrow bend of the hoe can be used to precisely pick small individual weeds out around non-target species. This may be useful in situations when annual weeds

such as mustards (*Brassica* spp.) are growing around native wildflowers or other non-target plants. Triangle hoes are also easily used as precision tools because of their sharply angled edges.

The stirrup hoe is used to treat small- to medium-sized herbaceous weeds and herbaceous perennials that do not resprout. They do not work well on large annuals and therefore are not recommended when annuals are large and flowering. This is especially important late in the growing season, unless the soils are loose enough for the hoeing action to pull the plant out of the ground, or the roots are soft enough to be severed. However, it may be useful if the weeds have started to flower, but before seeds have matured, and when plants can promptly desiccate when severed. The blade may not sever large plants with a thick taproot, such as large cheeseweed plants (*Malva parviflora*) or large mustards (such as black mustard (*Brassica nigra)*, or short podded mustard, (*Hirschfeldia incana*). The tool is ineffective on woody species, except in the seedling stage.

In contrast to its limited utility in treating large areas, the stirrup hoe is very useful for treating low density weed infestations and very localized seedling flushes of weeds. If small patches of weeds are widely scattered over multiple acres or sites, such as in early detection rapid response situations, then using a stirrup hoe may provide an efficient use of labor, similar to using a grub hoe. Hoes are lightweight compared to mechanized tools, so when carrying a hoe, workers will not fatigue as quickly as if they were carrying heavier equipment such as a string trimmer. Similar benefits exist in terrain that is difficult to walk through, such as on slopes or unstable soils, where carrying a lightweight general-use tool is more useful and safer than carrying a heavier or sharp-bladed tool especially in the early- and mid-growing season.

This tool can be used effectively on many weed species with little personnel training in many situations, with little risk to adjacent workers. It can be a reliable tool for organizers of volunteer weed removal events. There are few, if any, public perception issues with using this tool; in fact, weeding is often associated with hoeing.

Special Tips

There are few if any variations on how a stirrup hoe is used — it is pushed and pulled to remove weeds, and for precision weeding the blade can be held at an angle. Some stirrup hoes have a wide blade to increase the amount of area worked with each stroke and have small variations in the curvature of the lowest part of the blade from rounded to flat to better work softer or harder soils, respectively. Flat-bladed “dutch” hoes must be pushed, not pulled.

Optimal Conditions for Use

The stirrup hoe works best early in the season when weeds are small, in soils without rocks or cobbles, and in flat to moderately sloped areas. The stirrup hoe may be a tool of choice if traveling long distances to a work site since the tool is lightweight, easy to carry, and has a small blade that is relatively small with a low risk of injury.

A stirrup hoe can be used in arid regions quite effectively as long as the soil remains loose enough to work. If the soil is hard, the tool can be still effective if severing the weed at ground level is sufficient to avoid resprouting.

Caveats

When using a stirrup hoe, workers must be able to identify the target species in the seedling stage through the vegetative stage before flowers or other diagnostic features are present. Detectability must also be high since treatments are successful when cutting an entire individual plant or a small clump. A stirrup hoe will not control the weed population if seeds on target plants have matured or will mature after cutting.

In hard, dry ground where the hoe cannot penetrate the top layer of soil, this technique may have limited effectiveness on plants that resprout when the stem is cut too high (such as short pod mustard or flax-leaved horseweed (*Erigeron bonariensis*).

Hoeing disturbs soil surfaces and is relatively non-selective. It may impact desirable plants and stimulate flushes of weed seeds exposed to light by disturbance.

Potential Hazards to Humans, Environment, and Cultural Resources

Human. Low risk. The stirrup hoe is a low-risk tool to use, with the main hazard being injury from being struck with the tool blade or shaft. Since the stirrup hoe is not lifted when used, this risk should be minimal. Closed-toed shoes or boots and pants may prevent or lessen injury if struck on the foot or leg with a stirrup hoe. Repeated pushing and pulling could lead to fatigue and sore muscles and joints. If used too aggressively, users may get blisters on their hands or may get fatigued quickly. Stooping can be an issue with a stirrup hoe and users should keep their back straight. If the handle is not sized properly, workers may bend too much at the waist when attempting to use the tool causing back strain. Longer handles may be purchased and fitted into the tool to alleviate this problem.

Cultural resources. Moderate risk. Since a stirrup hoe can potentially damage objects belowground it should be used with caution inculturally important areas.

Habitat. Low-moderate risk. Using a stirrup hoe can disturb patches of soil creating conditions where some weeds thrive, especially in high light environments. This tool can also disturb biological soil crusts in a wildland setting.

Sensitive species. Low-moderate risk. A hoe may damage the burrow of small animals.

Erosion. Low-moderate risk. Erosion would become a risk if a large group of people were intensively hoeing a single area, especially if the site were sloped, near a streambank that could erode, or on highly erodible soils.

Other Non-Chemical Methods to Combine With

The stirrup hoe pairs well with a grub hoe in the early and middle stages of the growing season in sites that are highly disturbed. This pairing works well because each tool is slightly more efficient at different growth stages and sizes of weeds. The grub hoe more effectively and easily chops larger and more fibrous weeds (see Grubbing with Hoes BMP), while a stirrup hoe is more effective on smaller thinner weeds and seedlings. In areas with woody weeds, hand tools that can treat woody weeds, such as weed

pullers, saws, and cutting tools (see BMPs for Manual Removal or Controlling Plants by Cutting) provide an effective pairing. For sites with a mix of annuals and weeds with a large taproot, a dandelion fork may be paired with a stirrup hoe.

When Not to Use

A scuffle hoe is not effective on weeds that have underground storage structures, such as nutlets, bulbs or tubers. The top of these plants will be removed, but the plant will grow back. In addition, a stirrup hoe should be used with caution when weeds form stolons or rhizomes or both, such as bermuda grass (*Cynodon dactylon*). The stirrup hoe will cut the top of the plant and some of the shallow roots may die, but fragments of these plants may re-root and grow again, potentially creating many small plants where a few large individuals were initially growing. This tool is also ineffective at killing vines, such as field bindweed (*Convolvulus arvensis*) or Cape-ivy (*Delairea odorata*), which may resprout or re-root from plant fragments. A stirrup hoe is not intended to cut through woody weeds, except for small woody seedlings.

A scuffle hoe does not work on rocky, cobbly or gravely soils and works poorly on steep slopes. The stirrup hoe can be used up to the edge of boulders to sever weeds, especially because it is not swung (in contrast to a grub hoe). The scuffle hoe is also not effective in thick, muddy soils, such as silty clays or clays. The tool cannot be pushed and pulled through a thick soil without significant force. It may not be an effective tool in most wet locations because many wetland or riparian weeds can resprout once cut, and a different technique may be required.

Photographs

A heavy-duty stirrup hoe (left) a light-duty stirrup hoe (right, Hula Hoe™ brand). Photo credit: Christopher McDonald.

A heavy-duty stirrup hoe cutting a young short-podded mustard (*Hirschfeldia incana*). Note the blade is being pulled just under the soil surface to cut the roots. Photo credit: Natalie McDonald.

A heavy-duty stirrup hoe being used to precision weed around California buckwheat (*Eriogonum fasciculatum*) seedlings. Note the blade is held at a 30-degree angle and the corner of the blade is used to pull out the adjacent weeds. Photo credit: Christopher McDonald.

A triangle-shaped scuffle hoe. Some designs have a diamond shaped head and may be called a diamond hoe. Photo credit: Rogue Hoe Distributing.

A dutch push hoe-type scuffle hoe being used to clear grass seedlings in loose soil. Photo credit: Claire F. Meyler.

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1.4 Severing Roots

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Additional contributors: Garrett Dickman

Overview

Severing roots, also known as shovel shear and subsurface cutting, is a technique for severing the roots of plants just below (up to a few inches) the root crown and soil surface. It functions by completely separating the portions of the plant that harvest light from the portions that harvest water and nutrients. This starves both portions of the plant from needed materials and the plant dies if the stem cannot produce more roots and the roots cannot produce more stems.

This technique is useful for control of annual and young perennial weeds which are interspersed in areas with higher native plant cover. It is typically applied in areas where cover of the target species is low and minimizing disturbance to soil and surrounding vegetation is a priority. It can also be used in areas where the soil is fairly hard, making pulling difficult or impractical. Cutting through the soil just below the surface protects the soil structure below. The space required to maneuver the tool is small since the tool travels only the distance required to slice through the roots.

This technique can be useful where precise work is needed to not damage surrounding plants and is generally low impact with regard to cultural resource concerns because of the precision of the work. It is also not vehicle dependent as you can walk to the treatment site carrying the necessary tools. When used alone, in ideal conditions on ideal species, it is an effective control method. This is, however, highly scale-dependent as larger areas and infestations may require more personnel and time. It can also be used as a follow-up control method on seedlings and very young perennials in working toward eradication. If a large-scale treatment of another method has been implemented, this is an ideal way to conduct follow-up removal work.

How to Use

This technique works by severing the plant below the root crown to prevent crown sprouting. A sharp, sturdy tool is driven through the ground at an angle where it travels completely through the main root. This is most efficiently implemented with a tool and conditions where this can be done with one strike per plant. It is highly selective and most efficient when done well before the target species sets seed and when the biomass can be left in place. It is an effective control method on annuals and very young perennials (where severing the root still requires little effort).

To implement this technique and sever a taproot, place a sharpened tool at the base of the plant, angling under the stem, and push it as far below ground as possible. To prevent sprouting, the taproot should be severed below the root crown. The tool should enter and exit the soil in a straight line, without a digging motion. If done correctly, the severing motion should not disturb much soil at all. Depending on the species, it may be possible to feel the resistance when the tool passes through the

root and know when it has been severed. The plant may fall over on its own immediately after severing, which is also a good indicator.

The tools used for this technique vary by target root size, precision needed, and user comfort. Various tools used are: hori-hori, lettuce knife, kitchen knife, steak knife, weeding pick, forked weeder, sharpened flat-ended shovel, trenching shovel, spade shovel, fire shovel, root slayer shovel, pickaxe, and mattock. Sharpness, angle, and end shape are important decision makers when choosing a tool. Notched "v" tips are a very effective end shape.

The angle is important for worker ergonomics. A tool with a shape that can be used without much added motion from normal carrying is preferred (angled more for tools used while standing than for knife-like tools). Sharper tools will cut better but may dull quickly in gravelly soils.

As each plant is treated individually, this technique is highly selective. Non-target damage is only expected if the non-target species is growing close enough to the target species that its roots could be injured by the severing stroke. This is roughly the width of the tool used, so hori-horis and knives will have less impact than larger shovels.

This method works best in environments open enough to be easily moved through as it saves time. Many tools can be carried easily or be used as walking sticks when not in use (being cautious of sharp ends). It can be effective any time of year, but will be slower if done after seed production when the biomass cannot be left behind.

This method works mainly on plants with tap roots, including many annual and biennial thistles (including *Carduus nutans*, *Cirsium vulgare*, *Dipsacus* species, *Onopordum acanthium*, young *Cynara cardunculus*, *Gysophila paniculata*, *Arctium lappa)*, as well as *Pastinaca sativa*, mustards, young castor bean, young tamarisk, and many rosette-forming tap-rooted forbs. Note that mature *Cynara cardunculus* (artichoke thistle) will resprout when roots are cut.

Special Tips

Make sure tools are sharp and stay that way. Carry a hand file or sharpener in the field to maintain this.

In harder soil conditions or with thicker roots, a larger shovel can be set in position and kicked to sever the root. If driving a shovel by boot, shovels with wider footrests are preferred. While slightly heavier, they can reduce foot pain and boot wear from repeated striking. However, in instances where multiple kicks are necessary per plant this technique will rapidly become more tiring and less cost effective.

In wet conditions, modification can be made by holding the plant while cutting and then bagging or tossing it to a drier area. This is because some plants, especially those with thick roots, can re-root into wet soil and continue growing. This is most effective with small numbers of plants.

For larger trees, such as tamarisk, a scaled-up, more impactful version of this technique involves cutting deep below ground and backfilling the resulting hole up to one foot deep to prevent resprouting. This approach is also mentioned as part of the Manual Removal BMP.

Optimal Conditions for Use

Severing is especially effective in drier site conditions, as wet areas support plants that are more prone to resprouting. It is best done before seed is mature enough to ripen on severed stems so they can be left in place. Optimal conditions would be an infested area with clustered patches or scattered low density target plants interspersed with desirable vegetation. Optimal soils are fine (sandy, silty) and uncompacted types with little to no larger material (cobble, etc.). Flat to moderate (<40%) slopes are preferred as they allow safer movement with sharp tools.

Caveats

Plants growing in very wet conditions have more resprouting potential and are therefore often not successfully controlled with this method. Severed stems may be able to reestablish. Reduce this risk by moving stems away from soil. Likewise, this technique may have a lower efficacy in areas with higher annual rainfall.

Severing underground structures can be difficult in deserts, wetlands, and rocky soils. While this technique works well in dry conditions, it does not do well in dry, hard, clay soil where it is difficult to get a sharp tool through the ground. Soil must be soft enough to allow the cutting tool to be pushed through by hand or boot power and must not be so wet that plants left on the soil surface will be wet enough to root again.

This technique is counterproductive on rhizomatous perennials, perennials with fibrous roots (e.g., perennial grasses), or species that reproduce by underground vegetative structures (bulbs, tubers, nutlets, etc.).

Some species can resprout from taproots (e.g., artichoke thistle). This technique can prevent seed production but will not provide full control. Repeat visits will be necessary.

Large infestations are labor intensive and may be more feasibly controlled with other methods. Under optimal conditions a one- to two-person crew can handle a quarter acre of net infested area in a day. Larger areas and higher densities become demoralizing, time consuming, and may increase the risks of repetitive stress injuries. Severing underground structures also does not outpace populations with a high rate of spread.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety: Moderate risk. Hazards include cutting risks by workers using sharp hand tools. On steeper slopes, it will be safer to use versions of this technique which involve kneeling rather than standing. Repetitive stress injury will be the most likely injury for this method. Wrists, elbows (bursitis), and shoulders may be affected. Because work needs to occur low to the ground, persons may either be kneeling or standing, which leads potentially to stooping and back injury, especially if larger plants are being severed. Longer handled sharp tools require care when working in close proximity groups to avoid striking each other when carrying them during travel (e.g., turning quickly with shovel over shoulder). Maintain a suitable safe distance between workers and ensure they have any PPE associated with the chosen work tools, such as gloves and eye protection, where necessary. Also ensure workers are trained to use these tools safely in relation to the individual environmental hazards of the work site.

Cultural resources: Low risk. Because severing underground structures does not involve significant soil disturbance it is not likely to disturb cultural resources. Nonetheless, cultural resource experts should be consulted prior to initiating work if a site is located near to a cultural resource area of concern.

General environment: Low risk. There is little concern of hazards to non-target species or the environment because of the high specificity and minimal impact of this technique.

Sensitive species: Low risk. This technique penetrates the soil quickly. Care should be taken if there may be hibernating amphibians of concern in the area. However, this technique can be effective at fairly low depth soil penetration. Normal precautions should be followed to avoid nesting species.

Erosion: Low risk. If done properly, this technique minimizes soil disturbance by severing structures below ground and typically leaving them in place.

Other Non-Chemical Methods to Combine With

Severing underground structures may be used as a follow-up treatment for seedlings or saplings after other techniques have been used for initial control of larger tree or shrub species or for high-density removal. Large-scale high-density treatments can become less cost effective toward the tail end of a project when weed populations are spread out. At that point, this technique can be quite useful. As the tools are light to carry, it is useful to combine this technique with site visits for other purposes to opportunistically control outlier target plants.

When Not to Use

This technique is ineffective on established perennials and species with bulblets or corms that readily resprout. In some cases, underground severing can actually promote spread of these plants. It also cannot be used in extremely rocky soils, extremely hard soils, or under very wet conditions.

Photographs

Severing pigweed roots using a hori-hori. Note minimal disturbance of ground. Photo credit: Shani Pynn.

Severing tree tobacco roots using a sharpened shovel with minimal soil disturbance. Photo credit: Shani Pynn.

Severing spurge roots using a sharpened shovel with minimal soil disturbance. Photo credit: Shani Pynn.

References

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Supplementary Information

None.

1.6 Whole Plant Removal with Large Equipment

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Overview

Large equipment consists of machinery such as bulldozers and backhoes. Under the right conditions, with appropriate permissions, and with a skilled operator, whole plant removal with large equipment is an effective method for not only removing entire plants, but often the surrounding seed bank as well. This method can be effective on virtually all plant types and forms, regardless of phenology, flowering, or germination. Digging with large equipment is generally not suitable for areas with intact surrounding desirable vegetation unless this vegetation can be easily re-established or protected. Soil compaction that results from using heavy equipment can negatively affect revegetation efforts if not addressed. Use of heavy equipment is usually not cost effective in situations with low invasive plant cover. It is limited to stable, accessible terrain or areas within reach of equipment situated on adjacent stable ground.

Annual plants and some shallow-rooted perennial plants can be removed with their roots by scraping the soil, which removes the top inch to several inches of soil and much of the weed seed bank. Vines, deep-rooted perennial forbs and grasses, shrubs, and trees more often require deeper and more targeted excavation. While effective, a thorough job usually results in significant soil and habitat disturbance. Also, equipment rental and operation are expensive. Therefore, this technique is typically reserved for extreme conditions under which other techniques will not work. For example, large equipment is highly efficient for large areas that need full restoration or re-landscaping, as in fields of pampas grass or other large, high-density, contiguous infestations where killing and removal of biomass is the essential first step to re-establishing desirable vegetation.

Because of the intensity of soil and habitat impact, permits are often required when digging. Underground infrastructure (such as gas, water, and electric utilities), soil stability, cultural resources, and wildlife can all be impacted.

This technique can be used for eradication but must be followed by maintenance to revegetate a site and ensure its seed bank is fully depleted.

How to Use

Heavy equipment comes in many shapes and sizes and can perform a wide variety of work. This technique of whole plant removal on a large scale can produce a ‘clean slate,’ removing all aboveground and belowground biomass. However, this outcome is rarely permissible or desirable unless a site is a future construction site or very intensive active restoration is planned as a follow-up.

Equipment can be used to pull out plants and their roots, dig out or scrape off roots, scrape herbaceous plants, and remove topsoil with its seed bank. Equipment that can be used for scraping and digging

include backhoes, skid-steer loaders (Bobcats™), and dozers. Suitable attachments for scraping include buckets, box scrapers, and rippers for loosening compacted soil. Attachments typically used for digging include either a bucket or a reticulating bucket. Any operator of excavation or digging equipment should be properly trained to use the equipment safely and effectively. Scraping and digging should be followed-up by regrading and replanting or seeding.

Scraping. Scraping can remove aboveground plant and shallow roots along with seeds in top layer of soil, a minimum of 1 inch. Deep scrapes can remove deeper roots, all aboveground material and soil seed banks.

In certain circumstances, the removal of nutrient-rich soil by scraping can benefit the establishment of native grasses, known to be more competitive than annual exotic grasses in poor soil conditions. This technique has been utilized effectively on serpentine soils at small scales where large equipment has not damaged surrounding areas.

Uprooting. Large plants like pampas grass and various shrubs and small trees can be pulled out with an articulating bucket on a front loader, plucked out with backhoe, dug out with a bucket attached to a skid-steer or backhoe claw, or pulled out with a chain attached to a tractor or truck.

Raking. Chain harrows pulled behind trucks/tractors can be used to perform a shallow till and rake to remove low-growing herbaceous plants and their roots. This technique leaves soil prepped for seeding or follow-up applications (see also Mechanized Tillage BMP).

The greatest constraints on the use of this technique are the amount of collateral damage, the expense, the dependence on suitable topography, and the availability of appropriate equipment and skilled operators. Proper use of heavy equipment requires trained operators, maintenance, and associated personnel for fire suppression and public safety.

Special Tips

After full plant removal using large equipment, competitive planting should be used as a follow-up. All sites should be revisited to either dig out, clip, or manually remove seedlings and any remaining resprouts that have been left behind. Make sure to secure all necessary permits to complete work and implement best management practices to reduce erosion and negative impacts to wildlife.

Optimal Conditions for Use

Large equipment is most suitable for flat, easily accessible sites with high invasive plant cover.

Caveats

- Wet conditions may make terrain too unstable to support equipment.
- Wet conditions increase soil compaction from equipment.
- The optics of this technique can create public concern. Use explanatory signage.
- Equipment is expensive, requires a trained operator, and can be difficult to obtain.
- This technique is carbon-intensive and creates local pollution from burning fossil fuels.

- Moving large quantities of soil requires best practices for reuse or disposal.
- Moving soil brings risk of moving *Phytophthora* soil-borne pathogens. It is important that equipment arrives on-site free of dirt and vegetative debris, and that equipment is cleaned before it moves to the next project. See http://phytosphere.com/ for more information.
- Off-road equipment may damage more habitat than it helps to protect by removing weeds depending on the site.
- Permitting will probably be needed.
- Heavy soil disturbance may create erosion.
- Heavy equipment use can result in fuel and oil leaks or spills. Spill kits should be on site and available for use.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. High risk. Operators and nearby personnel can experience fatigue, hearing damage, repetitive stress injuries, inhalation of exhaust and dust, etc. Equipment can also roll over on uneven terrain. Proper training and Personal Protective Equipment (PPE) are essential.

Cultural resources. High risk. Heavy equipment can damage cultural resources that are buried in soil or on the surface. Field surveys should be performed by a qualified professional.

Sensitive species. High risk. Ground-dwelling insects, birds, amphibians, and small mammals can all be harmed by heavy equipment. Work sites should be cleared by a qualified biologist.

Habitat. High risk. Removal of nesting habitat, structure, and cover for many wildlife species is likely with excavation. This method is very destructive and should only be used when the benefits outweigh these impacts.

Erosion. High risk. Due to significant soil disturbance, erosion potential is high, especially when work is performed during the rainy season or on slopes. This risk can be mitigated by implementing erosion prevention measures.

Fire. High risk. Heavy equipment can start fires if operated in fine dry fuels. Assess the fuel conditions on site and consult fire weather restrictions in your area. This risk can be mitigated by having fire suppression equipment on site while working.

Other Non-Chemical Methods to Combine With

Competitive planting is recommended as a follow-up technique in any area with substantial soil disturbance and low chance for natural regeneration. This technique can also be paired with manual removal after large equipment removal to remove resprouts or seedlings.

When Not to Use

- Wet, steep, or remote conditions.
- When sensitive resources are present.
- Without trained professional operators.

Video Demonstrations

Backhoe shrub removal: https://www.youtube.com/watch?v=CRCpZ_Ewfk8

Removal by chain: https://www.youtube.com/watch?v=rwTM_WIBMNQ

Chain harrow removal of herbaceous plants: https://www.youtube.com/watch?v=H7wRHccjr-A

Brush jaw removal of shrubs, pampas grass: https://www.youtube.com/watch?v=W3XUTkcCy18

Uprooting: https://www.youtube.com/watch?v=W3XUTkcCy18

Scraping and clearing: https://www.youtube.com/watch?v=ZZee5rxOeVE

Photographs

Utility bulldozer. Photo credit: Rodney Smith.

Skip loader with articulating bucket on front and box scraper on back. Photo credit: Rodney Smith.

Narrow footprint excavator for excavation work on and near trails. Photo credit: Adam Maywhort.

Hydraulic tree spade. Photo credit: Photo credit: Dane Jensen.

References

None listed.

Supplementary Information

None.

2.Controlling Plants by Cutting

This section includes a variety of techniques that are designed to remove plant tissue aboveground to exhaust plant resources and ultimately prevent resprouting. Many of these techniques need to either be combined with other techniques to prevent resprouting or need to be implemented repeatedly to be effective. They include:

- Cutting with Bladed Hand Tools.
- Cutting with Pruners, Loppers, Shears, and Saws.
- Cutting with Brush Cutters and String Trimmers.
- Cutting with Chainsaws.
- Mowing/Cutting with Larger Equipment.
- Stump Grinding.

2.1 Cutting with Bladed Hand Tools

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Overview

Bladed hand tools include a variety of implements with sharpened edges for cutting, including machetes, sharpened hoes, sling blades, sharpened shovels, double bladed weed cutters, serrated sickles, scythes, brush hooks, hatchets, and axes. They are all used to cut vegetation above the ground.

The selectivity of a bladed hand tool varies with the type of tool being used and the skill of the user. A skilled worker, for instance, can cut weeds around natives with a machete or serrated sickle without harming natives or themselves.

Bladed hand tools, though very effective at cutting vegetation, can be hazardous to use without proper safety training. The heavier the blade and shorter the handle, the greater the risk of cutting to the operator. When workers use any bladed hand tool, they should wear sturdy shoes, long pants, and work gloves to reduce risk of injury.

The general philosophy of using cutting tools for invasive weed control comes from the understanding that plants get energy from photosynthesis. Repeated removal of aboveground biomass can eventually kill the plant by starving the roots of carbohydrates. Under the right conditions and with the right timing, cutting with a bladed hand tool can also limit the reproduction of invasive plants. With persistence, this technique can be used to eradicate small stands of certain weeds. It can stop the expansion of some non-natives along the edge of an infestation. With the exception of the brush hook, hatchet, and axe, bladed hand tools are typically used to cut fleshy, herbaceous vegetation. Woody vegetation can be cleared using a brush hook, hatchet, or axe (e.g., for fuels management), but these tools are not typically used to permanently remove or control plants. See the BMP for Cutting with Pruners, Loppers, Shears, and Saws for guidance on control of woody plants using repeated cutting.

Cutting with bladed hand tools is a technique that is especially valuable when soil disturbance should be minimized, either because of a weed seed bank that would otherwise be triggered to germinate, or because of sensitive biological or cultural resources. It is considered a long-term management technique that requires persistence over several seasons and trained, skilled workers to be effective. Cutting must be timed properly and occur multiple times a year for most kinds of plants to effectively limit reproduction and spread.

Bladed hand tools are often used as part of an integrated management program to target small patches of weeds. Their use, while effective, can be quite labor intensive, and for dense patches of weeds covering larger areas there are often better tools to choose (see Cutting with Brush Cutters and String Trimmers BMP). With that being said, they are lightweight, easy to use, and can be an ideal choice for weed control for smaller and more remote areas.

How to Use

Bladed hand tools can be used at any time of year for cutting back non-woody species, but their use must be carefully timed to effectively control a stand of weeds. Cutting should occur before a plant goes to seed and, for most species, multiple visits per year will be needed to eliminate seed production. If plants have already begun to set seed, cut material may need to be bagged and taken off site to ensure that seeds are not spread on site. Plan on returning to the same site for multiple years to target regrowth and new plants recruited from the seed bank. In sites that have remnant native vegetation, careful removal of non-natives is often enough to allow the natives to return to dominate the site.

Annual plants are chemically triggered to die once they reproduce, so a carefully timed single cut low to the ground late in their development — at bud stage or early flowering — can stop reproduction of individual plants and kill them prematurely under the right conditions. Cut as low as possible to the ground to reduce and delay plant regrowth. Multiple cuts per growing season may be needed to ensure seeds are not set, with more cuts per season being required in areas with higher precipitation. The number of rounds of cutting for an annual like black mustard can vary widely from only requiring one basal cut at flowering to needing up to four cuts in a season depending on rainfall, timing of cutting, and regrowth after the initial cut.

Perennial plants will require multiple treatment visits per season to stop reproduction and control plants, depending on plant type, timing of cutting, and timing and amount of annual precipitation. Rainfall is highly variable in semiarid regions of California and throughout the state among different habitat types. Some sites may need to be visited monthly or even weekly to ensure seed set does not occur. Root systems of rhizomatous perennial vegetation may not be effectively controlled through cutting.

Although cutting technique should be customized to each type of bladed hand tool and type of vegetation being cut, there are basic rules of thumb to follow to increase efficacy and reduce worker risk. Cut as low to the ground as possible to eliminate all green tissue aboveground, unless only seed heads are being targeted. Never swing a bladed hand tool in a manner that could inadvertently come in contact with your body or someone near you.

Machetes can be used to cut many types of vegetation by swinging the blade close to ground level to sever stems. Consider holding a stout tool or forked stick in your free hand to push vegetation away and expose stalks for cutting lower to the ground. Machetes that are toothed on one side can be useful to help grab the vegetation prior to cutting and to pull it out of the way after cutting. Modified hoes with square edges sharpened and tips cut off (see photo) work well for removing photosynthetic stems at ground level. These implements are useful for treating shorter vegetation without bending over. A double-edged weed cutter can be used to cut erect, fleshy vegetation (e.g., milk thistle and Italian thistle) and is operated by swinging the tool back and forth, keeping the blade low and level to the ground.

Serrated sickles can be used to cut back fleshy vegetation, vines, and even small twigs of shrubs. Pull the sickle towards you and rotate it around the base of the plant to fully utilize the serrated edge. Use serrated sickles after annual broad-leaf weeds become too large for hand pulling to minimize soil disturbance. Serrated sickles can also be used to cut grasses.

A sling blade or sharpened shovel can be used to cut fleshy vegetation, such as artichoke thistle (*Cynara cardunculus*). Although these tools work well for severing larger plants at ground level, sling blades in particular are heavy, less versatile, and not well-suited for small plants. They are sharp and heavy and can cause injury to the user if used improperly. The hooked tip to a sling blade is helpful for removing cut vegetation.

Scythes are useful for controlling annual grasses and certain fleshy broadleaf plants. Experienced users have found the Eastern European pattern scythe, designed for cutting grass crops, is more effective than the British Seymour-style scythe that is more commonly sold in the United States. Scythes should be used in a sweeping motion near the soil surface, where higher cuts may not effectively cut the target vegetation. This tool can be difficult to use effectively in areas of uneven, rocky terrain and requires training to use. Maintain a 10-foot spacing between workers for safety.

Machetes and sling blades are particularly dangerous to use for untrained workers. Workers should cut only in front of their bodies. Never reach out to one side or the other to make quick clean-up cuts in such a way that the blade is moving toward your legs and (in the case of machetes) your hand. Never grab a fistful of brush with one hand and swing the machete with the other.

Cutting tools must be sharpened regularly. Before sharpening, use a hand block sander (like Sandflex™) to clean the blade with a circular motion, removing "gunk"). Sharpening hand tools is best completed before going out to the field using a vice and a file in the shop. In the field, use a diamond hone — first the coarse (blue) side with a rotating motion on both sides of blade and then the fine (red) side to finish.

As an example of the effectiveness of bladed hand tools, consider the experience at Audubon Starr Ranch (in Orange County, CA) controlling artichoke thistle, a large, tap-rooted perennial. Cutting was found to be effective over two years if repeated cutting occurs from November through end of May at 3-week intervals in Year 1 and at 4-week to 8-week intervals in Year 2. Regrowth from the seed bank is controlled thereafter by cutting at 4-week to 8-week intervals, depending on site conditions. First year cutting uses brush cutters with heavy string. Subsequent cutting uses modified cutting hoes. (A sharpened angled hoe can also be used to cut off rosettes of bull thistle, ox tongue, and sow thistle. Other practitioners use modified shovels in a similar manner by bending and rewelding the shovel like a hoe and sharpening the cutting edges. Some similar tools are now commercially available.) Experiments on timing for cutting leafy rosettes showed no significant difference between initiation of cutting at first resprouting after rains versus initiating cutting at bolting stage.

Special Tips

Optimal timing and frequency of cutting may not always be known for a specific species, site, or environment. Experiment with cutting frequency and monitor regrowth over multiple seasons to optimize your cutting schedule for reducing or preventing seed set. Work sites can be numbered and then scheduled on a work calendar to keep visits regular. Keep in mind that changes in rainfall patterns will affect timing and frequency of cutting needed to be effective.

Bladed hand tools often work best for cutting plants once they have bolted and when they are "top-heavy," so they easily fall aside upon cutting. Know when target species bolt and bloom to optimally time cutting, especially if you cannot maintain a repeated cutting schedule.

Serrated sickles can be modified to be long-handled tools by attaching a pole (e.g., PVC pipe) to them to get into areas with thorny vegetation or poison oak.

Consider marking tool handles of your tools with florescent paint to avoid losing them in the field. Weathered wooden handles can be treated with linseed oil to rejuvenate the wood and reduce the risk of splinters.

Optimal Conditions for Use

Even terrain is optimal for cutting at ground level. Areas need enough room for workers to swing the bladed hand tool. Time cutting before a dry period to help reduce regrowth (rain stimulates regrowth).

Caveats

Multiple and regular cuts are required for multiple years for cutting with bladed hand tools to be effective as a weed control tool. This repeated cutting is expensive, time consuming, and hard work. Patience, consistency, and persistence are necessary for using bladed hand tools effectively as a management tool.

If weeds are already flowering when cut, flower heads may still be able to set viable seed and therefore may need to be bagged. Cutting plants that have already gone to seed may increase seed shatter and increase the distribution of these invasive plants. For any species, understanding the soil seed bank dynamics is critical for planning a long-term control strategy. Like any management approach, allowing seeds to be produced one year can undo years of seed suppression.

Invasive grasses may not be the best species on which to use bladed hand tools for control. Grass meristems (growth points) are typically low to the ground, below the cut line. Suppression of grass growth and seed production can be achieved through cutting, but species elimination and control will often fall short.

Perennial rhizomatous species, such as Canada thistle or perennial pepperweed, are not effectively controlled by cutting with hand tools regardless of precipitation. These species may be cut at the bud stage, multiple times per year, for multiple years and still not kill the root system (aboveground biomass and seed production will be suppressed but not controlled).

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety: Moderate risk. Bladed hand tools can cause injury from cutting if used improperly. Machetes, in particular, should only be used with extensive training and are not recommended for volunteers. Any sharp implement that will easily cut through a thick plant has the potential to cut the user or someone else. Some implements like a sharp shovel inherently have less risk than other implements like a serrated sickle or a machete. It is important to use these tools in a manner such that the blade does not move towards the user or others in the vicinity. Wearing boots, gloves, pants, and long sleeves will help protect the user. Caution must be taken when cutting species that have the

potential to be toxic (such as myrtle spurge or poison oak) so the user does not expose themselves to toxic saps or oils).

Cultural resources. Low risk. Because bladed hand tools cut aboveground plant material, they are not likely to damage cultural resources at or below ground level.

Habitat. Low risk. Bladed hand tools are typically used for precision work and therefore do typically pose a threat to habitat. If they are used on larger patches of invasive plants the impact to habitat increases.

Sensitive species. Low-moderate risk. Check sites before cutting to avoid disturbing nesting birds. No weed control should be done when ground nesting birds are breeding on site.

Erosion. Low risk. Because bladed hand tools cut aboveground plant material and keep roots intact, risk of erosion is minimal.

Other Non-Chemical Methods to Combine With

In larger areas which have been treated with a mower or a string trimmer, bladed hand tools can be good choices for follow-up to treat regrowth or plants that were missed. Sharpened hoes can be good follow-up for perennial, tap rooted, rosette species like artichoke thistle after initial mowing.

When Not to Use

Do not use this technique to target rhizomatous perennial species. These plants will continue to send up shoots from their extensive root systems, even if multiple cuts are made. Cutting these species once can stimulate new growth from lateral roots, increasing patch size and density.

Photographs

A variety of bladed hand tools that can be used for invasive plant management. Snake chaps in foreground. Photo credit: Doug Johnson.

Serrated machete, sheath, and belt. Photo credit: Sandy DeSimone.

Serrated sickle. Photo credit: Collin Raff.

Two modified tools for removing artichoke thistle rosettes. Left: Triangle hoe with tip cut off and edge sharpened. Photo credit: Sandy DeSimone. Right: Shovel bent, welded, and edge sharpened. Photo credit: Claire F. Meyler.

Left: Double-edged weed cutter and axe. Photo credit: Jutta Burger. Right: Cutting grass with a scythe. Photo credit: Claire F. Meyler.

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2.2 Cutting with Pruners, Loppers, Shears, and Saws

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Overview

Repeated cutting of plant stems with pruners, loppers, shears, or saws is a technique for invasive plant control that can be effective over time, depending on the type of plant being targeted and the frequency of cutting. It removes aboveground biomass and starves roots and other belowground storage structures if leaves and stems are kept from regrowing. Single cuts to remove seed heads are also standard practice to stop seed production.

Repeated cutting is useful in areas where the density of the target weed is low, where ground disturbance should be minimized, and where a target weed is interspersed with native vegetation that could be damaged by other control techniques. Cutting at short, regular intervals is essential for this technique to be effective at reducing target species cover over the long term. This technique is not typically used alone to control weed species because it is very labor intensive and requires repeated follow-up.

Pruners, loppers, shears, and saws are considered must-have tools for manual weed work by most practitioners. There are many different types from which to choose. Pruners (often called hand pruners) are used with one hand and can cut woody and rigid herbaceous stems less than ¼ to ½ inch-thick. Loppers have long handles that require two hands to use. They are typically 1 to 3 feet long and are used for thicker, hard-to-reach stems where more leverage is needed. Pruners and loppers are available as anvil or bypass types. Anvil types have one blade that cuts through the stem against a flat surface (the "anvil"). Bypass types have curved blades that overlap when the tool is closed to cut using a shearing motion. Hedge or grass shears have long blades and function like scissors. They are used with two hands and are designed to cut thin, fleshy, and fibrous stems. Shears can be used to control grass reproduction at flowering and before seed set. Pruning saws come in various shapes and styles. Most now have blades with teeth sharpened in both directions to cut on both the pull and the push stroke. Larger teeth saw through tough wood more quickly. Longer blades provide more cutting surface but are also prone to break if twisted while cutting. Smaller-bladed saws are available with fold-up blades that can be transported long distances safely. Longer bladed saws often come with a scabbard that can be fastened to your leg for safe transport. When buying any tool, weigh the benefits of a high quality and durable tool with ease of carrying it and the risks of damaging or losing it in the field.

Although a single cut with pruners, loppers, shears, or saws typically will not kill a plant, cutting can be valuable, even vital, in combination with other techniques to achieve effective weed control. It is often critical as a stopgap measure that controls seed production until more comprehensive approach to weed control can begin.

How to Use

Repeated cutting removes enough aboveground biomass and photosynthetic resources over time to exhaust and kill a plant. Stems (typically 3 inches or less but can be larger when a saw is used) are repeatedly cut low to the ground until the plant dies. Alternatively, the first cut can be made higher (at 1 to 2 feet above the soil) to encourage regrowth higher up and make recutting lower easier. Low recuts can be more effective but can result in multiple stump sprouts that are difficult to recut with hand equipment. Higher initial cuts are often preferred for large stands of shrubs (e.g., broom) and may expose a stem enough to allow plants to be removed subsequently by weed wrench. However, high initial cuts should not be made if the site is not being revisited in the same season to recut or otherwise retreat stems. Shrubs and trees may need one to several cuts per growing season for multiple years to keep regrowth down and deplete carbohydrate reserves in belowground structures. Given that this technique relies on stopping seed production as well as growth of target plants, practitioners should make sure that seed production is also controlled in adjacent areas to prevent reinfestation. Woody vegetation that can sprout from roots should not be targeted with this technique unless extensive repeated follow-up cutting can be guaranteed. The size of the area that this technique is effective on depends on the size, availability, and reliability of the work force over time.

Thorny vines, such as Himalayan blackberry, are best controlled using long-handled loppers (or see Cutting with Bladed Hand Tools BMP) in combination with follow-up manual removal or subsurface cutting. Biennials and herbaceous perennials that bolt (e.g., thistles) can be controlled by cutting bolting flowering stalks repeatedly. They will probably require multiple cuts in a single growing season to prevent flowering and often two years to kill plants. Depending on the species, cuts may stimulate regrowth (including root sprouts) that will need to be addressed, either by cutting or by another treatment method.

Cuts should be made straight across stems to avoid creating vertical spikes that could impale people, wildlife, or livestock. Stems cut near public use areas should also be either cut flush to the ground or removed promptly with a weed wrench to avoid creating tripping hazards or opportunities for other injury.

Cutting is more effective when it is done in the dry season. For instance, some French broom shrubs cut in the summer under drought conditions have died after only a single cut. Loppers with ratcheting capability and telescoping handles are particularly useful for cutting broom species because long handles can allow the user to access to the central stem and ratcheting increases leverage.

Cutting shrubs and trees leaves behind a lot of biomass. Biomass can be stacked as brush piles where it will provide some habitat and decay slowly over years (but these piles can also become hotspots for invasive plants and should be monitored). In some settings, brush piles can be burned during the wet season to reduce fuel loading on the landscape if proper precautions are taken and air quality restrictions permit burning. In areas with high fire risk, where re-establishment of desirable vegetation could be impacted, and where biomass might impact visitor experiences, biomass should be either chipped or mulched on site or removed. On steep slopes, cut biomass can be repurposed for erosion control, especially when baled as fascines or chipped. Plant material can also be used to close social or access trails created by control work. If plant material contains seeds, it should be removed from the work site or treated so that seeds are inviable.

Gloves are very important to wear when using cutting tools. Choose gloves with rubberized palms to increase your grip and reduce the chance of getting blisters. All metal-bladed equipment should be well maintained, cleaned frequently, and oiled to prevent rust from occurring on the metal surfaces. Clean off dirt and vegetative debris from tools, sharpen blades periodically, and disinfect them between species and project sites. A pocket file can be used to sharpen blades in the field. Oil blades and wooden handles periodically.

Special Tips

- In areas with strong browsing pressure, like from deer, mature shrubs may be cut below the browse line and deer will generally eat any new growth, thereby reducing or eliminating seed production. This works particularly well on shrubs in the Rosaceae family (*Cotoneaster, Pyracantha, Crataegus*).
- Target plants are easiest to find before the first cut. Mark sites and individual plants to minimize the chances that you will miss any when you return.
- Peel bark of stem bases to the soil line (or below) to reduce the chances of a shrub or small tree resprouting. This approach is especially useful for shrubs (e.g., broom) on steep slopes where manual removal with a weed wrench is dangerous and could promote erosion.
- Loppers can be purchased with telescoping handles, which can extend the reach to targeted vegetation. They can cut stems up to about 1½ inches in diameter but are most effectively used on smaller-diameter stems.
- Both loppers and pruners can be purchased with a ratchet feature that makes cutting easier. Presence or absence of a ratchet, gape size (how wide the blades open), sharpness, and length of handles all influence how large a stem can be cut. Bypass pruners are preferred for live stems because they cut tissue more cleanly and with less tissue damage. However, they are more prone to be damaged because the blades must fit closely, and pruner blades can easily become misaligned if the user twists them or tries to cut stems that are too thick. This is especially true for bypass loppers because the long handles increase torque on the blades. For this reason, some practitioners recommend using the anvil form (especially for volunteer groups). Pruning saws and loppers can be purchased as pole saws for difficult-to-access plants.
- Consider painting tool handles with bright paint or tying them with flagging tape to minimize chances of losing them in the field.
- Find a safe and efficient way to carry your cutting tools in the field. See https://www.cal-ipc.org/resources/library/videos/tool-belt/ for toolbelt tips.

Optimal Conditions for Use

- Best used for woody-stemmed plants that have a limited capacity to resprout. Cutting is particularly effective on conifers, which typically cannot resprout (exceptions include junipers and redwoods).
- Also effective as a stopgap measure to stop seed production for one season.
- Most effective during lower rainfall years that increase the stress imposed on a plant by cutting.

- Timing cuts for late in the growing season when energy stored in roots is low can increase effectiveness of limiting resprouts.

Caveats

This technique requires long-term and consistent follow-up. For this technique to be effective, stems that have been cut must be recut regularly (as often as every few weeks) for multiple years to deplete resources, depending on the species.

While the tools used for cutting are easily transportable to remote locations, consistent follow-up is especially difficult at those sites because of the additional travel time involved to access target vegetation.

The biomass that accumulates from cutting can create additional fuels for wildfire, depress establishment of desirable plants, crease hotspots for weeds, and may be considered unsightly.

Regrowth and next generation recruits that are smaller and less apparent than adult target plants are more difficult to detect. As with most other weed control techniques, follow-up searches are critical if your goal is to eliminate a weed from an area.

This technique can result in the removal of nesting habitat for birds. Nesting bird surveys should be performed between February 1 and August 31 to mark any active nests to avoid before work. In shrubland habitat, consider replanting with desirable plant alternatives if you anticipate impacts to wildlife.

Repeated cutting in wetter environments is more labor intensive and will take longer to be effective because more resources are available to plants to resprout.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. When sawing, cut away from your body; when using clippers, keep fingers out of their path. Wear gloves to reduce chafing and the risk of potential cutting. Reduce risks of carpel tunnel and hand or wrist strain by using ergonomically correct tools and taking regular breaks during work activity. Identify and avoid poison oak!

Cultural resources. Low risk. Cultural resources are generally not impacted by this technique because it does not disturb the soil surface. Cultural resources located on the surface may be exposed by work.

Habitat. Low risk. This technique is minimally invasive to habitat. If dead plant biomass generated is not removed from the site, it can be stacked away from waterways and in a manner that will minimally impact desirable vegetation. If mulched or burned, there may be short-term impacts to habitat.

Sensitive species. Low-moderate risk. Damage to wildlife and plants is a low risk with this technique if proper precautions are followed. Nesting bird surveys should be conducted before cutting during breeding season (generally February 1 to August 31) to minimize damage to nesting habitat. Identify sensitive plants in an area in advance and avoid trampling or otherwise impacting them.

Erosion. Low risk. Since soil surface is generally not disturbed, risk of erosion is minor. Keep soil surface covered with litter or other vegetation.

Other Non-Chemical Methods to Combine With

Repeated cutting can be used with other techniques that target emerging seedlings, such as flaming, hoeing, or manual removal.

Cutting is often used to make other techniques possible. For example, tarping, cutting subsurface structures, manual removal with a weed wrench, or grub-hoeing may require removing tall stems first.

Cutting can also be used as a one-time measure to shift the competitive balance from the target plant to that of co-occurring desired vegetation. This is generally only effective for pines, palms, and other species that do not resprout.

Cutting can be combined with bark peeling (see Girdling BMP) to improve its efficacy.

Lastly, cutting is a useful way to remove seeds, canes that root at tips, and seed heads to prevent propagule dispersal in a project area, regardless of other techniques being used for effective control.

When Not to Use

Repeated cutting should not be used as the sole technique on rhizomatous species because of the tremendous amount of sustained effort that would be needed to be effective. Some rhizomatous species will actively spread more when cut. Also, this technique should not be used on any stump- or root-sprouting woody species (e.g., tree-of-heaven if retreatment cannot be guaranteed) because single cuts may make later control more difficult if regrowth is not removed.

Video Demonstration

https://www.cal-ipc.org/resources/library/videos/techniques-for-controlling-woody-plants/

Photographs

Bypass loppers used to cut Acacia at Zyante Sand Hills. Photo credit: Ken Moore (2009 video still).

Anvil pruners used to cut Acacia. Photo credit: Ken Moore (2009 video still).

Pruning saw being used to cut down Acacia. Photo credit: Ken Moore (2009 video still).

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Supplementary Information

None.

2.3 Cutting with Brush Cutters and String Trimmers

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Overview

String trimmers and brush cutters are widely used power tools. A favorite tool of urban landscape maintenance crews, their use is also common by vegetation management crews in natural landscapes and open spaces. These tools are used to sever vegetation at or near the soil surface.

String trimmers or brush cutters consist of a spinning cutting implement on a handheld pole powered by either gas or electricity. They are typically mounted on a shoulder harness. The cutting implements are often interchangeable to varying degrees depending on the manufacturer and model of the particular trimmer or brush cutter. String trimmers use a plastic string which cuts by whipping against upright plant stems. String thickness should match the robustness of the target species. Most string trimmers can dispense more string by bumping the head on the ground during operation. More robust string can be used with fixed heads (not a bump feed) for thick-stemmed or mixed plant communities. For woody and thicker-stemmed dry weeds, plastic or metal blades can be used. Blades range from single fixed semi-round blades to multiple articulated individual blades. Metal blades can also be used to target smaller diameter woody vegetation. Personal protective equipment, such as long pants, gloves, and eye protection should be worn during operation. Metal-bladed trimmers and brush cutters can create sparks that cause fire. Always use precaution when using powered equipment in dry conditions.

How to Use

Select the appropriate string or cutting head for the target species and install according to the manufacturer's specifications. Hold the trimmer so that the cutting head is near the ground and start the trimmer. When using, keep the cutting head as close to the ground as possible and move it side to side to sever the stems. If there are desirable plants, stop the blade from spinning by releasing the throttle, or sweep the trimmer over the top of the desirable plants. Avoid trimming desirable plants when possible. Under dry conditions, where vegetation could catch fire, have a fire extinguisher and a response plan to reduce the risk of fire, especially when using metal blades which can strike sparks if they hit rocks. Using plastic blades or string will greatly reduce fire risk.

Treatment frequency to eliminate seed production differs depending on the target species and climate. For annual species, this will be as many times per year as new populations germinate or regrow after initial cutting. For perennial species, this will be once or more during the growing season depending on the level of control desired. Certain broad-leaf perennial species and grasses may need to be cut back three to four times a growing season to prevent seed production. Annual or biennial plants should be targeted just before or at flowering. Cutting needs to take place before seeds are mature enough to finish setting. For most grasses this is before the "milky" stage of seed development.

Perennials should be cut in the vegetative stage, just before flowering begins, and multiple cuts will be needed to prevent seed production. For all species, secondary and tertiary growth throughout the season may begin to flower at a much shorter height and frequency than the initial spring growth. Experimentation may be needed to determine what combination of timing and treatment interval is necessary to achieve suppression for an individual site or species. Revisiting the sites every two to four weeks may be necessary to control regrowth throughout the growing season.

When working with taller vegetation, multiple cuts or very rapid cutting passes may be needed to avoid the stalks falling on the cutter. Depending on the accumulated amount of vegetation being cut, it may be necessary to remove the vegetation from the site using rakes or other tools to release desirable vegetation. Slash piles may also be an effective alternative when material cannot be removed off the site.

String trimmers are most effective at smaller sites to ensure that target weeds are cut at the optimal stage in their development for maximum suppression. Utilizing a string trimmer or brush cutter may be useful for controlling resprouts following other control techniques, such as mowing or felling trees with a chainsaw. Likewise, this technique's effectiveness can be improved by hand pulling, grubbing, or using herbicide to manage regrowth or plants that were missed to ensure seed set does not occur.

String trimmers and brush cutters need to be maintained according to manufacturer recommendations for optimal function. Two-stroke gas powered equipment should be run with the correct octane fuel mixed with the specified ratio of oil for good performance. Carburetors and sparkplugs should be routinely maintained, and gearboxes should be properly lubricated. Adequate string should be loaded into the cutting head at the beginning of the day and metal blades should be kept sharp for good performance. For battery operated equipment, correct charging and discharging specifications should be followed to maximize battery performance and longevity. Read and follow all manufacturer instructions to ensure the equipment lasts and performs out in the field.

Special Tips

One way to improve the effectiveness of string trimmers or brush cutters for weed suppression is to roughly mulch weeds during the cutting process. This can be achieved by bringing the cutting head down sideways over the cut stems multiple times as they lay on the ground after initial cutting. Alternatively, mulch cutting can be achieved by making multiple cuts, starting at the top and trimming small portions of the plant as you move down the stalk. Mulching material during treatment may take more time, but in certain instances may be beneficial. Mulched material covers bare soil and helps vegetative material decompose quicker.

Invasive perennial bunch grasses may be effectively suppressed by turning the cutter at an angle and trimming deep into the crown. Additional follow-up will be needed to control secondary growth from the sides.

String trimmers may also be used to "scalp" the soil surface when controlling annual weed species. As the string is flexible, the cutter can be used at an angle bringing the string in contact with the soil surface (not in rocky areas). Seedlings, or established low-growing vegetation, can be brought down to the soil

surface creating bare ground with the scalping method. Scalping the soil surface can be a good site preparation before restoration activities.

Circular blades can be used on brush cutters to clear small-diameter woody or very fibrous vegetation. Typical blades will allow 2 inches of cut, for a total effective use on vegetation with stems less than 4 inches in diameter. When targeting woody vegetation, a slow directed use of the blade is needed, compared to the swinging motion used when targeting other vegetation. Either a string trimmer or brush cutter can be used to cut suckers or sprouts from larger woody vegetation which was felled with a chainsaw. Cutting these sprouts may need to be done multiple times over a few seasons for suppression of the root system. If proper precautions are taken in moister environments where fire danger is low, a metal blade can be used to cut and mulch dry materials for fire clearance in areas where weeds have already dried. Heavy string can sometimes be substituted in place of a metal blade to reduce the risk of fire.

When using solid blades, make sure to ease into cutting thicker vegetation. If the cut is made too quickly, there is possibility for the blade to bounce off the target vegetation. Only use blades designed for brush-cutting. Do not use circular saw blades, as they are not designed to handle the impacts that occur when brush-cutting.

Optimal Conditions for Use

Flat dry sites are ideal conditions for the use of string trimmers or brush cutters. However, they can also be used effectively on a variety of vegetation in rougher terrain and may be the best option available for vegetation suppression on steeper slopes. Gravel, rocks, and cobbles can be problematic, inhibiting effective cutting, especially with metal blades.

Sites which are dry typically need to be cut less often for weed suppression and vegetative growth. It is better to cut at the appropriate timing for the target species and before the dry season occurs. Often, especially for annual species, there will be limited regrowth potential if precipitation does not follow a cutting event. Wetter sites will often support a much higher level of vegetative growth and will need to be cut more frequently, often on a set schedule to suppress the vegetation to limit reproduction. Vegetation that is very wet or excessively dry can be more difficult to cut. A year-to-year cutting schedule may need to be altered based on precipitation received.

Caveats

One assumption of using a string trimmer is that the target weed species is not closely intermixed with non-target desirable species. If desirable and undesirable vegetation are intermixed, using a string trimmer may have negative impacts to desirable vegetation. While string-trimming may still be appropriate, the impact to desirable species should be weighed against the benefit of controlling the invasive plant. Off-target impacts can be especially great if multiple cuts are planned throughout the growing season to suppress the invasive species.

When vegetation becomes dry, and there is any potential for the generation of sparks, metal-bladed trimmers should not be operated. While plastic-bladed and string trimmers have less potential to generate sparks, fire danger still exists both from sparks and from a hot motor coming in contact with

dry vegetation. Care should be taken with all gas-powered equipment during and after operation, as the hot exhaust from the machinery is a potential ignition source. Electric or battery powered string trimmers may be a viable alternative when fire risk is high. Lastly, as with any equipment, it is important to clean the equipment (especially cutting heads) after each use and to make sure the operator is not moving weed seed through clothing or equipment.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety: Low to moderate risk. Using a string or blade trimmer has potential to cause harm to humans operating the equipment and standing in the vicinity of operation. String and blade trimmers can generate flying debris, which could injure the user or someone close by. Direct contact with the cutting head is not common, as it is extended on a shaft, far away from the user. It is of upmost importance to use proper personal protective equipment (PPE) including, but not limited to, eyewear or face shield, long pants or chaps, hearing protection, and gloves. If used for extended periods of time, using a harness and padded gloves will reduce fatigue and back strain from holding a vibrating tool. Repeated long-term use of this equipment can cause repetitive stress injuries. Steep terrain can increase the risk and hazard associated with using the equipment. Equipment typically uses a gasoline and oil mix, and extended exposure to fumes can cause nausea and other health risks. Wearing a particulate or organic vapor respirator can minimize the user's exposure to fine particles from mowing, exhaust particulates, and toxic fumes. Anyone planning to use a respirator for work in the state of California must follow Cal-OSHA guidelines and work for an employer who is compliant with Cal-OSHA employer guidelines. Caution should be taken when string-trimming weeds that have foliage or sap that may cause contact dermatitis. It is always important to wear proper PPE when string-trimming, but even more important when targeting species associated with contact dermatitis.

Cultural resources: Low risk. As there is minimal soil impact utilizing this equipment, generally the risk for impacting cultural resources is low.

Habitat: Low to moderate risk. This technique will remove vegetation various species depend upon. Removing small, low-density weed infestations will have minimal impact, whereas cutting large monocultures will have more negative impacts.

Sensitive species: Moderate risk. Pre-disturbance surveys should be conducted before brush cutters or string trimmers are used in areas where sensitive species occur. In instances where sensitive plant species are intermixed with the target weed, there is potential to injure them when using the equipment. Sensitive plant species should not be cut. When ground nesting birds are present, these areas should be avoided to protect nests from noise, direct damage, and flying debris. If the vegetation to be trimmed is dense and there are concerns for frogs, rodents, etc., a site can be cleared with the help of a biological monitor. Alternatively, impact to these species may be reduced if the trimmer can be used in a top-down manner to allow species to flee. Verify species that may be present before beginning work to determine if this is appropriate and review and use accepted avoidance procedures (e.g., 100-foot buffers around actively nesting bird species) to minimize impact. Gas powered versions are motorized and can disturb birds and other wildlife both via physical disturbance and through noise (although this is not usually a severe disturbance).

Fire: Low risk (string trimmers), Moderate risk (metal-bladed brush cutters). Metal blades can create sparks when they hit rocks or other hard objects. Wildfires have been started by brushcutting. Do not use metal blades under high fire risk conditions and always have assistance and extinguishers on hand to address ignitions from sparking.

Erosion: Low risk. This technique poses little erosion risk as it leaves the belowground plant structures intact and causes minimal soil disturbance. If large acreages of plant material are cleared on steep slopes, there is some increased risk of erosion occurring. Mulching plant materials that are cut may help cover the soil surface and reduce the risk of erosion.

Other Non-Chemical Methods to Combine With

String trimmers or brush cutters can be used in conjunction with a variety of other techniques to combat specific weeds. Suckers from trees that have been cut with a chainsaw can be effectively targeted with a brush cutter. Brush cutters can also be used to follow up and clean up plants that could not be targeted with a mowing operation.

As string trimmers and brush cutters often do not control the species they cut, but instead suppress the vegetation and seed production, it can be good preparation for follow-up work with manual removal, grub hoeing, and other techniques to kill the target plant. Brush-cutting can also be used as site prep for tarping, solarizing, or mulching when done low to the ground.

When Not to Use

Perennial vegetation that spreads by rhizomes or other underground reproductive structures will not be controlled by cutting with a string or blade trimmer. Aboveground growth may be suppressed with repeated applications, but the roots may continue to spread, and resprouting along spreading roots may be encouraged after the initial cut is made.

Additionally, any species that reproduces via aboveground stem fragments (e.g., Japanese knotweed, bermuda grass, Cape-ivy) should not be targeted with a brush cutter or string trimmer because pieces of the aboveground vegetation can be spread with the potential to reroot and establish multiple plant populations.

Do not use this technique under red flag wildfire conditions. Do not use a metal blade under fire-prone conditions.

Video Demonstration

[https://www.cal-ipc.org/resources/library/videos/brushcutter/]

Photographs

Left: Bump-head line trimmer attachment. Right: Heavy-duty brush cutter with metal circular blade, U-shaped handles, and harness. Photo credit: Tom Getts.

Three weed trimmer head attachments for tougher vegetation. Left: Heavy-duty fixed-line trimmer head. Photo credit: Shawn Thorin. Center: Tri-bladed brush cutter blade. Photo credit: Shawn Thorin. Right: Circular brush cutter blade (for woody material). Photo credit: Tom Getts.

Heavy-duty polyline to be used with fixed-line heads for fibrous vegetation. Photo credit: Shawn Thorin.

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2.4 Cutting with Chainsaws

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Overview

Chainsaws are typically used to control woody plants with large stem diameters. They are used by professionals and private landowners to fell trees, but not by volunteers because they require a high level of training and skill to operate safely.

In California, large established stands of tree-of-heaven or eucalyptus are often targeted species (although resprouting species such as these require follow-up work). In the Modoc Plateau region of California, junipers are often targeted where range and shrublands are easily invaded by trees in the absence of disturbance by fire. Chainsaws can be used to cut down virtually any kind of aboveground woody biomass. Multiple return visits will be necessary on plants that have the capacity to resprout for control to be achieved.

Numerous sizes and styles of chainsaws are available, with various advantages to each. Larger saws may be needed for large vegetation but saws with 12- to 14-inch bars are suitable for most invasive plant control. Smaller saws are lighter and are often preferred by users to limit fatigue over a long day of work. Large invasive tree removal may require larger, heavier saws with bar lengths ranging from 18 to 40 inches.

Most chainsaws are gas-powered, but some are electric. Gas chainsaws have two-stroke engines which require a high-octane gas mixed with oil (typically at a 50:1 ratio; read your tool's manual and follow fuel recommendations for optimum performance). Though more powerful, gas chainsaws emit fumes such as benzene and carbon monoxide that can be harmful to the environment and to workers. They are also loud. Electric chainsaws are either corded or battery powered. Battery powered electric saws are typically smaller and less powerful than corded options, but they are lightweight compared to most gas-powered saws and are thus easier to carry to remote locations. However, smaller battery-powered chainsaws are limited by battery capacity, and extra batteries can be very heavy. Lithium batteries generally last longer than nickel cadmium (NiCd) batteries.

How to Use

When using a saw, it is important to maintain proper chain tension and sharpness. Adjusting the tension of the chain should be done when the saw is cool. The chain should feel snug, but still move freely, as a chain that is too tight can cause damage to the equipment. A chain that is too loose can pop off the bar during use and cause damage to the saw or injury to the user. The teeth on the chain should be sharpened regularly with the proper file, as a sharp chain will increase the effectiveness of the cut and reduce wear on the drive system. It is important to let the saw do the work, and not force the saw into the cut. Keeping the chain out of dirt and rocks can be difficult while making cuts flush with the ground

but is essential to maintaining sharpness. Sparks from the chain hitting rocks in the soil is a safety hazard during wildfire season (summer and fall) and should be avoided at all costs. Fire extinguishers should be on site during felling operations, and fire risk plans should be in place.

Chainsaws can be used to cut woody vegetation at the ground level. To utilize the saw safely, there needs to be access to the main stem and room for maneuvering around the vegetation. Trees and shrubs which have branches low to the ground may need to be trimmed back to create a safe space to initiate the cut of the main stem. Every saw has a chain brake to stop the chain from moving, and it is important to use the chain brake whenever a cut is not actively being made. Using a chainsaw can be dangerous without training. It is important when cutting large woody vegetation to use proper cutting technique such as front cuts, holding wood, and wedges. Use of these tools and techniques are not described in this publication, because they should be learned through sawyer instruction courses.

Woody vegetation can be targeted with a chainsaw at any time of the year, given environmental conditions that allow safe use of the machinery. Typically, coniferous woody vegetation (such as pine, juniper, or cypress) will not sprout after cutting and can be effectively controlled at any time of the year. When cutting coniferous species, it is important to cut the stem below any green vegetation to eliminate the potential of new growth.

Deciduous species are more likely to send up sprouts from roots or stump following the main stem being cut. Shoots from cut stumps can grow into new trees or bushes and can continue to produce seeds. Shoots can grow from stumps, root collars, or from root buds many feet away from a stump. It is important to conduct follow-up treatments to control these shoots either by cutting, tarping, or herbicides. If cutting is chosen, shoots must be cut multiple times per year, for multiple years, to exhaust the root system of energy. In some cases, targeting deciduous tree species before the dry season can reduce the vigor of regrowth.

Biomass from cut vegetation can be handled in different ways. Woody biomass can be left on site, piled and burned, chipped, or removed from the location. Different techniques vary greatly in cost and labor and must be considered during the planning process. Your biomass strategy will depend on assessments of factors including fire risk, impact on re-establishment of desirable vegetation, and aesthetic impact on visitor experiences.

Follow all maintenance and operational recommendations for equipment. Regardless of power source, all chainsaws require bar oil to provide lubrication during cutting. Running a saw without bar oil can damage the equipment. It is important to regularly take apart and clean the saw to maintain proper function. See “Potential Hazards” for more information on safety precautions. Tree pathogens may also be spread by chainsaws and other tree pruning equipment. Clean and sterilize equipment after a job and before using equipment on desirable vegetation. Seventy percent alcohol, bleach solutions, or Lysol can all be used to disinfect the equipment from pathogens.

Special Tips

Chainsaws can be used in conjunction with other techniques and are often part of an integrated pest management (IPM) approach. For stumps that send up sprouts after cutting, physical barriers such as thick, dark tarps can be used to cover the stump and reduce growth. Tarps and the surrounding area

need to be monitored to ensure sprouting does not occur. For stump sprouting species, it may be of increased benefit to dig a hole around the stump and recut the stump below the soil surface. Covering the cut stump with a barrier and burying the stump and barrier should inhibit sprouts from the stump (see Tarping BMP).

For stumps left uncovered, cutting the regrowth from stumps and roots needs to be conducted multiple times a year for multiple years. Chainsaws may not be the best tools to cut regrowth less than 3 to 4 inches in diameter. Loppers, saws, hedge trimmers, reciprocating saw, or brush cutters may be more appropriate for smaller shoots. For shoots that sprout around the stump from existing root stock, mowing with various equipment may be most appropriate to suppress growth.

Chainsaws can also be used to facilitate other treatment methods by removing excessive biomass. Biomass removal can provide access to roots and rhizomes which can then be removed using hand tools. This technique works well on large grasses such as jubata grass (*Cortaderia jubata*) and giant reed (*Arundo donax*). Additionally, maintaining low vegetation cover at a project site can facilitate follow-up treatments for species where consistent follow-up is critical, such as Cape-ivy (*Delairea odorata*).

Battery-powered reciprocating saws are another useful hand tool for invasive species control. While not as powerful as chainsaws, reciprocating saws are often lighter, more portable, and generally require less training for safe operation. Smaller diameter woody stems, or the crowns of invasive grasses, can be effectively cut using a reciprocating saw. Multiple batteries will be needed for full day use.

Optimal Conditions for Use

Chainsaws can be used effectively under both dry and wet conditions. Large, woody vegetation generally recovers quickly after cutting in wetter climates, so frequent cutting and control efforts may be required in wet areas. Most woody species in dry areas do not grow as quickly as vegetation in wet climates, so control efforts may not need to be as frequent. For some woody species, cutting before the dry season reduces the amount of sprouting from the root and stump.

Caveats

Cutting resprouting species a single time will not provide adequate control and may make the problem worse. Careful planning for follow-up treatment of suckers is essential.

By removing large woody vegetation, one opens the canopy and newly available light resources may encourage invasive species colonization. Secondary invasions should be anticipated during the management planning process.

The growth form of the target species should also be considered during the planning phase and should be matched to the skill and training of the sawyers tackling the problem. Large trees on steep slopes generally require more skill and training to cut safely. Additionally, multi-stemmed branching species are more difficult to cut than single-stemmed or straight-stemmed species. Sawyers should not work alone and should be in radio contact with other crew members in case an injury occurs during the felling process.

When treating woody vegetation, there must be adequate resources to deal with the biomass generated, especially when treating and dealing with large trees. In essence, removal may need to be treated as a logging operation, even if there is not economic value to the woody vegetation being removed. Removal of the biomass by off-site chipping, on-site chipping, or piling and burning are some of the options that can be utilized. However, almost all methods from biomass removal to burning increase the opportunity for disturbance on the landscape being treated. From skid trails to burn marks, it may be necessary to follow up with additional treatments to reduce secondary invasion or species replacement. Restoration planting and follow-up control may be required to ensure desirable vegetation takes hold in these disturbed areas.

Operation of chainsaws in a wildland setting often means bringing gasoline, oil, and bar oil into the field, which can be hazardous to water quality and the natural environment if spilled. A tarp or similar non-permeable surface should be used to contain spills while refueling your chainsaw. A spill kit should be on-site or nearby to quickly address any accidental spills.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety: High risk. Chainsaws can be very dangerous to use, and proper training and personal protective equipment is needed for all users. This cannot be overstated. There is no substitute for hands-on chainsaw safety training prior to use of the tool. Vibration-absorbing gloves, protective eyewear, hearing protection, and chainsaw chaps should all be used. Direct severe physical injury from the saw or chain is possible, even to experienced sawyers. Injury can also occur from large woody vegetation that is being cut. Trees can fall in an unintended direction or fall off the stump unexpectedly if cut improperly. Chainsaw users must understand forces of tension and compression to predict how trees will react to different cuts. It is always important to have clear footing and an unobstructed path of escape while cutting. Fuel exhaust from gas-operated chainsaws is also hazardous and exposure should be limited to the degree possible.

Cultural resources: Low risk. In general, cultural resources should not be impacted by the use of chainsaws. Care should be taken to avoid contact of the chainsaw with anything other than the non-desirable vegetation. Falling trees can potentially damage aboveground cultural resources, if present. Precautions should be taken when cutting to ensure the felled vegetation will not contact or damage such resources. Additionally, in some locations, non-native trees may be considered historic resources (e.g., eucalyptus windrows on historic ranches). Tree removal in these situations should be coordinated with cultural resource specialists.

Habitat: Moderate risk. Animals living in target trees (such as birds, bats, and squirrels) may be harmed by cutting. Trees should be checked, and nesting bird surveys should be conducted before cutting during breeding season (generally February 1 to August 31) to minimize damage to nests. Do not cut trees that contain active nests.

Sensitive plants: Low risk. Identify sensitive plants in the treatment area in advance and avoid trampling or otherwise impacting them.

Erosion: Low risk. There is little risk of increased erosion immediately after woody vegetation is cut. Stumps and roots are typically left in place after cutting. However, there can be a risk for increased

erosion, especially on steep slopes, if other vegetation does not colonize the site before large rain events. Likewise, techniques used to deal with cut biomass — such as slash pile burning, removal, or mulching using large equipment — may increase the potential for erosion. If erosion-prone conditions are created during treatments, logs and slash from the tree removal can be used to build erosion control structures.

Fire: Moderate risk. Using gas-powered equipment can cause sparks, so users should follow all local fire prevention guidelines and restrictions when operating chainsaws. Care should be taken to remove dead and dry materials around the trees, and fire extinguishers or water sources should be available at the cutting site.

Other Non-Chemical Methods to Combine With

Follow-up treatments of stumps after trees are cut with a chainsaw is often needed. Tarps or other physical barriers can be secured over the stump to prevent resprouting from occurring (see Tarping BMP). Follow-up control of sprouts with cutting hand tools, brush cutters, or other stem removal techniques may be required if herbicides are not utilized. Excavations of woody stumps will be more feasible once the aboveground biomass has been cut. Stumps can be ground down after cutting to prevent resprouting (see Stump Grinding BMP).

When Not to Use

Using a chainsaw to control woody vegetation that sends up stump or root sprouts will not be effective if secondary sprouts are not planned for and controlled. Cutting the main stem will reduce seed set and greatly suppress the plant, but it is important to follow up with secondary cutting treatments for sprouts and suckers. Sprouts may need to be cut multiple times a year for many years to kill or suppress the root system of the tree. In certain climates, suckers must be treated monthly to prevent root system recovery. If sprouts are not controlled, cutting an individual stem or trunk may lead to further spread through generation of sprouts forming off the auxiliary roots. Adequate funding for follow-up treatments and monitoring should always be part of the initial control plan.

Photographs

Left: Fourteen-inch bar gas-powered chainsaw, the most commonly-used size range for woody invasive plant management; held here for scale, and not to be used without proper PPE. Photo credit: Cal-IPC archives. Right: Mid/large-sized gas-powered chainsaw for larger trees. Photo credit: Tom Getts.

Chainsawing Russian olive and regrowth six months after cutting (Colorado). Photo credit: Tom Getts.

Reciprocating saw. Photo credit: Joan Miller.

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Supplementary Information

None.

2.5 Mowing/Cutting with Larger Equipment

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Overview

Mowing is one of the most common and useful non-chemical weed control techniques for large areas. Mowers come in a variety of shapes and sizes for many types of situations. There are two categories of mowers: tractor-operated mowers and push behind mowers. The most commonly used tractor-operated mowers are brush hogs and flail mowers. Brush hogs have thick, dull blades that spin horizontally under a wide deck, typically dragged behind a tractor. Flail mowers use a set of vertically spinning flat blades to cut vegetation. Like rotary mowers, many flail mowers are often dragged behind a tractor. Specialty mowers, both rotary and flail types, can be operated on an extended arm to mow side slopes and roadsides. Typical push behind mowers include rotary mowers, either with a blade positioned under a deck (e.g., lawn mowers) or a brush mower blades, or flail mowers. Push behind mowers are also available with plastic string as the cutting implement mounted under a deck.

Mowing typically cuts vegetation a few inches above the ground, though some flail mowers can cut vegetation down to the soil surface. Mowing is most often used in flat, even terrain, or in areas with gentle slopes. However, some specialized mowers that can be operated by remote control are now available for uneven surfaces and steeper terrain. These pieces of equipment have tracks instead of wheels and have specialized flail mower heads or rotary decks.

Mowing is commonly used throughout California to non-selectively suppress vegetation in a wide variety of environments such as roadsides, pastures, and parks. Well-timed, intensive, multiple pass mowing throughout the season can control invasive species on a large scale. Mowing can also be used as a site preparation technique for restoration in wildland settings. In general, mowing is a good tool to suppress all vegetation quickly across a large area. However, “quick” vegetation suppression can only be achieved in specific types of terrain and ground cover. Mowing can also be used to delay seed set of an invasive plant in preparation for tarping to ensure seed set does not occur. As with all forms of heavy equipment use, cleaning off debris between sites is necessary to minimize the spread of invasive plant propagules.

How to Use

Mowing can be a good way to suppress vegetation that is not large and woody. In areas with woody vegetation, specialized equipment such as masticators can be used.

When mowing invasive plant species, proper timing and frequency of mowing are essential to prevent seed set from occurring. Annuals should be targeted at the flowering stage but before seed set. Many species of annuals, such as foxtails and yellow starthistle (*Centaurea solstitialis*), can regrow and produce seed after the initial cutting. A single cut per year will not control any species that sends up

secondary growth and flowers after cutting, whether annual, biennial, or perennial. If only one pass is made, the lowest mowing height will offer the best weed suppression. If a second cut is planned, mowing at a high initial cutting height will allow space to come back and make a second cut below the height of the original cut. Mowing two or even three times in a growing season with decreasing cutting height may be necessary to achieve seed head control. Often, resources only allow for a single mowing pass over the site.

Biennial species can be targeted in a similar fashion as annual species by mowing right before or at flowering. As with annual species, secondary regrowth may occur, and multiple passes may be needed to suppress seed production.

Vegetative perennial species will often resprout after an initial cut and multiple cuttings per year may be needed for seed suppression. Mowing will not eradicate resprouting perennial species, but suppression can be achieved.

Smaller woody brush species can effectively be mowed and suppressed with a large rotary mower operated at a high cutting height. Ideally, sites should be mowed multiple times a year for multiple years to prevent seed set from occurring in the targeted weedy vegetation.

Wetter sites will often support a much higher level of vegetative growth and will need to be mowed more frequently, often on a set schedule to suppress vegetation and limit seed production. A single cut in higher precipitation zones will not offer good suppression of most species. Dry sites will have less regrowth potential of all species after the initial cut.

Mowing feasibility is limited by terrain and groundcover, both for the equipment powering the mower and the mower itself. Slope, rocks, and large woody vegetation limit where the equipment can be effectively used because uneven terrain, rocks, and woody debris on the ground can contact mower blades and damage the machinery.

Both rotary and flail mowers can be damaged by striking solid materials during the mowing process. Rotary mowers have a cutting height fixed above the ground and are not as likely to come in contact with the ground and solid materials. Flail mower blades can be dropped closer to the ground and are more likely to contact soil and rocks at low cutting height operations. If the mechanism is not damaged, individual flail blades can be replaced if damaged. Generally, cutting height needs to be kept higher for larger equipment compared to small mowers.

Mowing uses machinery with gas engines and spinning blades can generate sparks, especially where rocks are present. Mower operators should always have the proper fire suppression equipment ready at hand. Whenever there is a risk of starting a fire, spotters and water trucks should be on site.

Special Tips

Different mowing heights can influence the effectiveness of invasive plant treatment. For example, in areas with native perennial grasses invaded by annual broadleaf plants, a high mowing height can suppress the annuals while releasing perennial grass species to compete with weeds.

Timing of mowing is critical, not just for invasive species seed suppression, but for selecting which vegetation is favored by the management action. Timing mowing to maximize impact on the target

invasive plants must be weighed against the timing when desirable species may be in growth stages which are sensitive to being cut.

Mowing repeatedly can select for short species such as non-native basal-rosetted annuals and biennials released from competition.

In instances with thick thatch layers — such as with invasive species like medusahead and perennial pepperweed — mowing can help break up and manipulate the thatch layer which favors the invasive plant. Manipulation of these thatch layers through mowing or other techniques can release native species present in the understory.

On flat ground without rocks, flail mowers can be used to scarify soil in preparation for restoration. This technique, referred to as scalping, is at the interface of mowing and cultivation. However, contact of the flail mower with the soil surface also greatly increases the likelihood of damaging the equipment.

Mastication is a form of mowing that turns woody species into mulch by grinding stumps and small brush down to the soil surface. This can be a very effective technique for woody species that do not regrow after being cut. For species that send up stump suckers or auxiliary root suckers, mastication will only provide temporary suppression and will need to be followed by additional control methods such as pruning, brush-cutting, or herbicides. The amount of woody vegetation to be masticated should be considered before treatment. While some woody chip mulch may be desirable, thick layers of mulch can suppress both desirable and non-desirable vegetation and pose a fire hazard. Mastication is especially useful for removing live and dead canes from stands of Himalayan blackberry (*Rubus armeniacus*), but follow-up treatment is necessary to control this species in the long term. Mastication is also successful at reducing standing biomass from woody species such as brooms, which may be a short-term goal in fuel reduction scenarios, but brooms ultimately need follow-up treatment on resprouting stems.

Excessive slope can limit the ability to safely mow, but slope mowers are available to use on roadsides.

Optimal Conditions for Use

Mowing with large equipment is most effective on large areas with smooth, even terrain and easy road access. Soils should not be wet when using large equipment mowers as compaction can occur. Ideally, vegetation to be mowed will not be covered in dew or rain but also not dried up. Smaller push behind mowers can often be used in tighter spaces on steeper slopes but generally require even terrain for use. For annual species, mowing at the proper time can help limit regrowth potential.

Caveats

Mowing can only be conducted when the terrain and moisture conditions allow safe operation of the equipment. Special heavy equipment operator licenses and training certificates may be required in some places for large mowers.

Spinning blades can strike rocks and other materials, which may create sparks and start wildfires. Chances of starting a fire are lower early in the season, and at higher humidity levels that typically occur earlier in the morning. Anytime there is wind, mowing operations should be cautious because fire risk

increases. For roadside mowing applications under high fire risk conditions, a water truck should follow mowing equipment.

Mowing may be limited in areas of steep slope. While there are specialized pieces of equipment which can handle steep slopes, not all mowers can be safely operated. Consult the operations manual and manufacturer of the equipment.

Weeds can unintentionally be spread by poor timing. Mowing weeds after they set seed can scatter their seeds, leading to an increase in the density of the target weed species. Furthermore, mowing can cause disturbance within the mowed area by opening the canopy to light, which stimulates sprouting.

Likewise, equipment may disperse weeds to the next mowing site if viable seeds are not cleaned from the equipment. Cleaning equipment between sites before transportation is essential to limit seed spread. Machinery should be cleaned on site, if possible, to ensure invasive seeds stay on site.

Mowing with large equipment should be avoided when sites are very wet following precipitation. The weight of the equipment can increase the possibility of getting stuck. Additionally, using large equipment on moist soil can cause soil compaction. For mastication of woody vegetation in areas where soils freeze, operation of large equipment during the winter can reduce the likelihood of soil compaction.

As with all cutting techniques, proper timing is vital to the success of the operation. Timing may vary from year to year with fluctuations in the weather. Proper planning is important to ensure the equipment and operator are ready at the optimal time for weed suppression. This is especially important when dealing with contractors. Time and resources should be budgeted to fix and maintain equipment throughout the season of operation.

Potential Hazards to Humans, Environment, and Cultural Resources

Human Safety: High risk. Safe use of equipment requires training and is essential to the operation of large mowing equipment. Proper personal protective equipment (dust mask, ear, and eye protection) should be worn by the operator and any individuals within the area. Flying debris and vegetation thrown by the mower pose an injury risk in the area. When using large equipment, there is a high risk of physical injury directly from the equipment itself during loading, hookup, and operation. Difficult and rocky terrain may pose more potential for user injury than flat level ground.

Cultural resources: Low-moderate risk. When abrading the soil surface, identify and avoid surface cultural resources. Cultural resources may be exposed by mowing or masticating. If they are at soil surface level, they may be crushed by heavy equipment.

Habitat: Moderate to high risk. Mowing will remove vegetation, impacting habitat for a variety of species depending on that cover. Impacts will range from moderate to high, depending on the size and frequency of the area being mowed.

Sensitive Species: Moderate risk. Rodents, reptiles, and amphibians may be harmed by mowing. Consider sweeping an area prior to mowing to move animals from the site temporarily. Ground and shrub nesting birds maybe be negatively affected if sites are mown during the breading season. Areas with sensitive plants are not appropriate for mowing with large equipment. For non-sensitive desirable

species, mowing can either be beneficial or harmful depending on the timing and specific species' response to cutting.

Erosion: Low to moderate risk. Mowing will leave belowground plant structures in place, but there is increased risk of erosion whenever aboveground vegetation is removed, especially on slopes. Additionally, soil disturbance from the machinery itself may make the site more susceptible to erosion. Frequent mowing with large equipment, or mowing on wet ground, can increase compaction. In areas where mowing height is extremely close to the ground or at ground level, the risk for erosion may be increased.

Fire: Moderate-high risk. Rotating blades can cause ignitions by sparks from blades hitting rocks. Always have assistance and equipment on hand to address ignitions. Do not mow during high fire risk conditions.

Other Non-Chemical Methods to Combine With

Mowing can be combined with several other techniques for successful invasive plant control. Mowing provides an opportunity for quick vegetation suppression which can be followed by tarping, hand pulling, grubbing, or cutting techniques. Mowing can also be an effective way to prepare a site for competitive planting.

When Not to Use

Many annual species will be suppressed temporarily by mowing but may then regrow and set seed in a shorter prostrate form. Continuous mowing will favor species with prostrate growth and may shift the plant community to lower growing plants. Do not mow where there are populations of undesirable low growing prostrate species, as these plants will have a competitive advantage when mowed. Mowing vegetation after seed set may lead to an increase in the weed population by stimulating seeds during the mowing process.

Rhizomatous perennial plants' aboveground growth may be suppressed by mowing. While seed set may be limited, only suppression will be achieved. Multiple cuttings are needed for suppression of the aboveground growth, but rootstock may or may not continue to reproduce and spread. Mowing rhizomatous species with a single cut during the growing season is not recommended. Multiple mowing passes per year for multiple years are needed to suppress populations of rhizomatous perennial plants. Some rhizomatous perennial grass species have been shown to decrease when mowed multiple times per year at the flowering stage. However, many years of mowing are necessary to achieve control of perennial grasses.

Photographs

Brush hog-type rotary mower with tractor. Photo credit: Tom Getts.

Flail mower with tractor. Photo credit: UC Regents.

Flail mowers can be used on heavy brush. Left: Remote-control flail mower. Photo credit: Jutta Burger. Right: Mature French broom successfully removed with flail mower. Photo credit: Pamela Beitz.

Left: Walk-behind brush mower. Credit: Quinn Sorenson. Right: Walk-behind mower with reciprocating blades. Credit: Claire F. Meyler.

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Supplementary Information

None.

2.6 Stump Grinding

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Overview

Stump grinding removes trees and large shrubs by chipping them to below ground level using a power tool with a high-speed, steel-toothed cutting wheel. Grinding is a way to control individual trees and thick-stemmed shrubs that otherwise resprout when cut. Grinding is not a control method on its own, as it requires removal of aboveground biomass first.

Cutting wheels are either vertical or, less commonly, horizontal. Grinders are gas-powered machines that come in many shapes and sizes. They can be walk-behind units that a worker rolls into position, dedicated drivable machines, or attachments to large equipment (e.g., backhoes). The most commonly used stump grinders are walk-behind and are usually available at big box hardware stores to rent. Stump grinding is generally less expensive and labor intensive than stump extraction, but still very costly and potentially disruptive to surrounding habitat.

Control typically requires only a single visit to grind down targeted mature plants. Trunks must be cut down to ground level prior to grinding and the stumps must be ground to below ground level for this technique to be effective. Grinding only targets the mature life stage of a woody plant and typically cannot be used economically or effectively on small trees or shrubs with trunks less than several inches in diameter.

Grinding will leave behind an excavated hole of wood chips and dirt as well as well as aboveground biomass from cutting. Site considerations may require remediation and biomass removal. The grindings that remain may suppress passive revegetation.

This technique can be used to eradicate a species at a small scale if plants are mature and at very low density. Limitations include site access and grade requirements, habitat disruption, cost, and operator safety.

How to Use

Stump grinding requires a skilled operator and many safety precautions. Before employing this technique, an operator must read and understand the entire manual for the grinder being used, get sufficient training to operate the equipment safely, and have appropriate personal protective equipment (PPE). Grinders available for rent are typically 25 horsepower and have a 16-inch cutting wheel. Transporting a grinder requires a vehicle rated to haul the machine's weight and a trailer hitch. Alternatively, tree service providers can be contracted to do the work. A single tree will cost from one hundred to several hundred dollars to grind.

Prepare the stump by removing all rocks from around its base. Trim the stump to be as flush to the ground as possible. When using a traditional grinder with a vertical wheel, raise the wheel over the front edge of the stump, start the wheel spinning and lower it into the stump to grind away no more than three inches (unless stated otherwise in the grinder's manual) of material at a time to avoid bogging down the engine. Swing the blade back and forth across the stump, grinding down wood as you go. Repeat this process until the hole is at least four inches below ground level to prevent resprouting. Fill the hole with soil and wood chips. Process aboveground cut biomass according to site needs.

Moderate slopes can be accessed from an adjacent stable, flat surface using a backhoe or similar equipment with a grinding attachment on an arm extension. Grinding to below ground level may be difficult on slopes because the grinder will be more difficult to position optimally.

Large, specialized vertical stump grinders are also occasionally employed for high intensity vegetation management, but their utility for wildland weed control is limited because of their size, cost, and destructiveness to surrounding vegetation.

The following links provide step by step instructions and illustrations:

https://www.popularmechanics.com/home/lawn-garden/how-to/a129/stump-grinder-tips/

https://www.youtube.com/watch?v=GspnPRorkEM

Special Tips

Be sure to remove any rocks at the base of the stump. Rocks will dull cutter heads quickly. Chips can fly far and potentially break windows or hurt people adjacent to your work area. You may need to put up barriers made of plywood or other material to stop flying chips.

Optimal Conditions for Use

Grinding requires a highly accessible site (or specialized equipment that can reach the site from an adjacent location that is accessible).

If the goal is to fully control a given species, grinding is most effective on target species that are not actively recruiting or when combined with other methods to remove younger individuals of the species.

Caveats

- This technique only targets mature forms of large woody plants and therefore should be either focused where recruitment is not occurring or combined with another method that can address young plants/seedlings.
- Heavy equipment should not be used on wet or muddy soil because it will compact soil.
- This technique is expensive and limited to accessible sites that are not steep.
- Some trees, such as acacia, mayten, and tree-of-heaven, resprout vigorously from extensive lateral roots. Stump grinding may not be effective for these difficult species.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Moderate to High risk. This equipment employs high-power spinning cutting blades and therefore should be handled with extreme care. Users should receive training prior to operating equipment and utilize all recommended Personal Protective Equipment (PPE) that include ear, eye, and face protection, as well as gloves. Follow all safety instructions in the manual or your agency guidelines. Prolonged use can also cause repetitive stress injury from vibrating handles. Prolonged exposure to exhaust fumes can increase a user's risk of cancer. Hearing loss without proper ear protection may be a consideration.

Cultural resources. Moderate risk. Heavy equipment could impact subsurface resources. Grinding, if not aimed specifically on tree stumps could impact surface-scatter or buried resources immediately adjacent to target plants.

Sensitive Species. Low to Moderate risk. Wildlife may be nesting in the trees being removed. Nesting bird surveys should be conducted before cutting during breeding season (generally February 1 to August 31) to minimize damage to nests. Wherever possible, use this technique outside of the breeding season. Negative impacts to non-target plant species pose a low-moderate risk. Identify sensitive plants in an area in advance and avoid impacting them.

Habitat. Moderate risk. Habitat alteration with this technique is high, but generally restricted to a small area.

Erosion. Moderate-High risk. Risk of erosion can be moderately high depending on equipment and site (steep slopes, low remaining vegetative cover) but is generally restricted to a small area.

Fire. Moderate to High risk. Equipment can create sparks which can cause fire. Minimize risk of fire by only using equipment during periods of low fire risk, removing rocks and other hard objects that could spark when hit by the blade, and having personnel with fire suppression equipment on site in case of ignition.

Other Non-Chemical Methods to Combine With

Stumps must be cut by either chainsaw or hand saw prior to grinding. Also consider pairing grinding with manual whole plant removal to remove other life stages of the target plant.

When Not to Use

Wet soil conditions will increase compaction and physical disturbance to a site by large machinery. Very dry, high fire risk conditions will increase the risk of fire. Rocky sites should be avoided.

Video Demonstration

https://www.youtube.com/watch?v=Y3h4n4f2_Y8

https://www.youtube.com/watch?v=GspnPRorkEM

Photographs

Grinding wheel in action and partially ground stump. http://www.stumpgrinding-mn.com/.

Stump grinding a residential tree (*Ficus elastica*). Photo credit: Dane Jensen, West Coast Arborists, Inc.

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Supplementary Information

None.

3.Controlling Plants in Place

This section covers techniques that are designed to kill plants in place without removing them. They use heat, in the form of flaming or direct steam application or by severing vessel connections of trunks in place. These techniques work well for small areas or individual plants but are limited in their effectiveness to particular plant size classes and growth forms. The BMPs in this section are:

- Flaming.
- Steaming.
- Girdling.

3.1 Flaming

Lead author: Pamela Beitz

Co-authors: David Thomson, Peter Frye

Additional contributors: Ken Moore, Darren Bressee, Patrick McIntyre

Overview

Flaming is used to control carpets of seedlings of broadleaf weed species that germinate together in large numbers and are localized in small areas. It typically involves sweeping a propane torch flame over very young plants, causing their cells to rupture from the heat. Flaming is most effective on seedlings from the cotyledon stage to the six true-leaf stage. The ability of this technique to outpace production of propagules is dependent on implementation of technique and timing.

Flaming was originally developed as a weed control technique by the agricultural industry to treat weeds in furrows using a tractor and a boom. It has only recently been modified to be used as a hand-held weed control technique for wildland and urban landscape settings. This method has a narrow range of conditions under which it can be applied effectively, including high site moisture (too wet to support fire), small spatial scale, accessibility to roads, and early phenological stage of plants. Despite this narrow range, it is a helpful tool to incorporate into an IPM program because it lengthens the weed treatment season by effectively targeting seedlings early in the season that would otherwise take more time to control manually. Flaming also has the advantages of not leaving plant debris behind and leaving soil surfaces intact. Flaming may have the added benefit of forcing germination of seeds in the soil. With follow-up treatment, this technique can shorten the longevity of the seedbank.

Flaming is intended to wilt a plant, not burn it. Burning with a propane torch takes significantly more time per plant than flaming, is not any more effective, and poses a greater risk of fire. Seedlings that have their growing tips aboveground and have poorly developed roots are the most susceptible. Grasses and other monocotyledonous plants with their growing tips at or belowground or at ground level are likely to regrow after flaming unless they are very young seedlings. Older plants with well-established root systems cannot be effectively controlled with this technique unless they have no capacity to regrow after being damaged. Plants that reproduce vegetatively cannot be controlled with flaming unless repeated treatments are used to deplete carbohydrates stored in roots below ground. This technique has been used effectively for seedlings of broom species, poison hemlock, stinkwort, yellow star thistle, and very young grasses. Broom seedlings in particular are highly susceptible when they are in the 3 to 4-leaf stage and younger and germinating synchronously.

Flaming can have non-target effects such as killing desirable plants in its path that are unable to regrow. Recruitment of desirable competitive species may be an important consideration in your long term weed management plan and should be considered. Alternatively, there may be very little desirables in the seed bank if the weed infestation is old enough to have exhausted other species. In this instance, there may be very little desirable species that can immediately recruit. Additionally, flaming has the potential to kill any ground-dwelling organisms immediately in the path of the flame.

Flaming should not be conducted in dry conditions or with excessive thatch that might catch fire. Fire extinguishing equipment (water and fire rakes) should always be on hand in the event that vegetation catches fire. Flaming is not generally recommended for seed bank control because of the high heat required to kill seeds. It is most efficient for small areas because it is both very labor-and fuel-intensive at larger scales.

This method is moderately expensive both because of the cost of propane and the labor to do the flaming and refill tanks. Furthermore, applicators need to incorporate down time if equipment freezes from prolonged use ("frost-up" due to gas expansion). Some areas will require site preparation to remove flammable debris.

Some practitioners also use propane torches to burn individual plants to kill their seeds at maturity before they are released. This late-season approach targets seed rather than growing plants and has been used effectively on barbed goatgrass. However, the risk to applicator and of fire spread is much greater with burning, especially late season, and should only be conducted with proper permissions, sufficient training, and appropriate protective equipment. It is not specifically recommended here.

How to Use

There are a variety of torches that produce different flame intensities. Weed control can be effective with 400,000-750,000 BTU burners. Several different cylinder (tank) sizes are also available. Non-agricultural applicators usually use a stand-alone 20-lb or higher propane cylinder with a hand-held torch attached with a hose. Larger/heavier cylinders can be used but need to be transported by ATV or dolly. Small-sized backpack propane tanks are also available. Hoses can be connected to increase accessibility. Note that tanks, hoses, and orifices can freeze up during use, so include plans for warmup periods or back-up tank/torch set-ups. Use quick release air couplers to trade tanks quickly or use larger tanks to reduce frost-up. Torch mounts are also available for vehicles and ATVs for larger areas but may have limited utility in a wildland setting.

Cylinders may be steel or fiberglass. Fiberglass tanks are lighter and generally considered safer. Torch arrays should include a POL valve to protect a tank from over-filling. All valves should be tightened securely. Torch wands should be ergonomic and light enough to minimize applicator strain. They should have a standing pilot light. Consider also using a torch with piezo-electric self-ignition for convenience. Prepare to have a sparking igniter if the built-in ignitor fails.

Before flaming, rake away organic debris to make flaming more efficient, to reduce risk of fire, and to avoid killing insects, reptiles, and amphibians. Perform a test burn to ensure that the flame will not carry in the vegetation where you will be flaming. To perform a test burn, as illustrated by Ken Moore (see flaming video link), scrape a small test plot in an area that is representative of your site. Scrape all vegetation off to mineral soil. Flame the vegetation in this burn plot. If the vegetation carries flame to the mineral soil line, this indicates that your site is too dry to use this technique at this time without risk of fire. For best results, plants need to have enough moisture for heat to burst tissue cells and cause wilting. Treated plants will become discolored and will bend or collapse. Ideal conditions are when target plants are moist enough to be scalded, rather than burned, by treatment. Even if you may have sufficient moisture in your test site, be cautious about gusting winds that may move burning materials

outside of this area, potentially starting a fire. Do not use this technique if wind is strong enough to dislodge debris.

Proper flaming technique involves passing the torch flame over seedlings in a slow, even motion. If plants have sufficient moisture, they will wilt as a result of being steamed, rather than burned. In rare situations (i.e., when conditions are safe, plants are susceptible, but too late in their growth stage to be vulnerable to steaming), plants will be singed instead, though this is less efficient and riskier and therefore not preferred.

Flaming can stimulate seed germination. If it does, it will require follow-up treatments later in the same season. For many fabaceous species (e.g., broom and acacia), multiple treatments will be necessary throughout mid-winter and early spring each year to ensure that most germinating seedlings are controlled. This technique can be used to flush the long-lived seed bank of some invasive species. Its lower efficiency may be offset by a reduction in the number of repeated annual treatments if the weed seed bank can be exhausted more quickly. Flaming must be conducted repeatedly over time until the weed seedbank is depleted for this tool to be effective over the long-term.

Special Tips

Species with highly synchronized seedling flushes are ideal for flaming because seedlings will all be of a similar age.

If weeds are flamed on steep or rocky terrain, tanks will need to be secured either by being mounted on a backpack or by otherwise being held securely to avoid rolling away.

Many practitioners recommend spraying seedlings with water in dry conditions ahead of time to increase efficacy by increasing heat conductance.

Flaming, though not very selective, can be fairly precise, so it can be used to kill small seedlings around already established plants to maintain desirable plant cover and minimize soil disturbance.

The valves on the propane tank will freeze up after continuous use. It is recommended to have two tanks and alternate their use. Do not use the flame to thaw tanks. Also, when tanks freeze, dirt, and mud with weed propagules can freeze to the bottom if it is contact with the ground. Be careful to clean the tank before moving or cradle the tank in a crate or other carrying device to avoid contact with the ground.

Optimal Conditions for Use

Moist conditions, low thatch cover, low to no wind, and seedlings at or younger than the 6-leaf stage (or less than 2-inch diameter rosettes).

Caveats

Because this technique uses fire, it can cause concern with some members of the public, as well as land managers. Ensure proper safety protocols are being followed and considering installing a temporary interpretive sign describing treatment to the public.

Flaming around poison oak or its litter can cause severe complications for people who are sensitive to this species. Under these conditions, applicators should consider being fitted for and wearing a respirator. Perennial grasses may be favored by flaming and burning because these techniques stimulate tillering and spread.

Thistles are not effectively treated by flaming. Even when still very young, they have deep tap roots and require 2+ treatments to die, making other methods more effective and efficient. Young shrubs and trees that have deeper roots may also resprout after initial wilting.

Flaming is difficult to use on summer germinating species because of fire danger under dry summer conditions.

When used over bare ground, flaming maintains bare surfaces but can also increase the risk of erosion.

Flaming is equally as effective for low-density invasive plant stands as for high-density stands but is more inefficient. Consider alternate techniques such as hand pulling or scraping for less dense stands.

Flaming can negatively affect desirable species in the treatment area. Identification of desirable plant species, angle of the flame, intensity, and timing can mitigate these off-target effects and increase selectivity.

Potential Hazards to Humans, Environment, and Cultural Resources

*Human safety***.** Medium risk. Skin burns are a risk for applicators. Clothing can catch fire. Flaming also creates fumes and smoke that can be inhaled.

Cultural resources. Low risk. Cultural resources are at low risk because this technique does not disturb the soil surface.

*Sensitive species***.** Low to medium risk. Flaming can kill insects, amphibians, and reptiles in the immediate treatment area. Applicators should flush a site prior to beginning treatment. Raking loose vegetation, duff, litter, etc. from the site will help achieve the same goal.

*Habitat***.** Low to medium risk. Loss of vegetation, duff, and organic material can negatively affect insects, amphibians, and small mammals. This technique is best in small scale so that habitat elements are not removed or disrupted in the environment.

*Erosion***.** Medium risk. Erosion may be a significant consideration since flaming treatment occurs during the rainy season and can result in bare ground. Take precautions to avoid erosion on steep slopes near streams and other water bodies.

*Fire***.** High risk. It is essential to perform flaming in moist conditions and with fire suppression tools nearby. Perform a burn test before beginning.

Other Non-Chemical Methods to Combine With

This technique is most effective when followed up by manual removal of plants that emerged after treatment or that did not die as a result of flaming. Where additional weed seed is stimulated to germinate, follow-up flaming can further reduce the seed bank. Mowing, raking, or brush removal prior to flaming will reduce flammable thatch and increase surface area for seedlings to germinate.

When Not to Use

Do not use flaming under high moderate or high fire risk conditions. Dry, windy conditions and sites with substantial dry thatch should be avoided. Avoid using flaming without prior surveys and employ avoidance measures if sensitive animals (arthropods or vertebrates) are known to inhabit a site. Consider materials for erosion control near streams, drainages, or waterbodies.

Video Demonstration

https://www.cal-ipc.org/resources/library/videos/flaming/

Photographs

Flaming with backpack equipment on young *Limonium ramosissimum*, Sausalito, CA. Photo credit: Drew Kerr.

Left: Under dry conditions, scrape a safety perimeter around the area you are flaming. Photo credit: Cal-IPC. Right: Flaming broom seedlings in the rain. Photo credit: Pamela Beitz.

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Supplementary Information

Some practitioners argue that weed species with higher seed production can be treated more effectively than those with lower seed production because they will typically germinate in large numbers and therefore be more apparent. This potential benefit should be weighed against the greater difficulty in being able to treat an entire population if it is already well established with a large seed bank.

Marshes are typically too wet to treat effectively because the saturated soil absorbs most of the heat from the torch. However, *Limonium* seedlings have been treated successfully in high marsh habitat. In this case, they were singed, rather than steamed. Flaming may be difficult and too risky to use in shrubland habitat because of the large amount of surface fuels present.

Although grasses are generally not effectively controlled by flaming, there are some exceptions. Flaming very early in the growing season can reduce annual grass cover without harming co-occurring native annual species that haven't germinated yet. Furthermore, one study had found that Japanese stiltgrass is effectively controlled over two successive years of flaming (see Ward and Mervosh 2012).

Whereas flaming is generally not considered effective on perennials, experiments in an agricultural setting suggest that some perennials could be reduced by >90% with three rounds of flaming. Grass control was not effective under these conditions. Timing of applications was critical in determining the level of efficacy. Propane use of 1.2 kg propane/km-1 was effective at reducing target broadleaf weeds early in their growth, but higher use of >2.6 kg propane/km-1 was less effective at later stages. High use of over 4.1 kg propane/km-1 was ineffective for grass species, regardless of their growth stage.

In drier areas, the optimal window for flaming becomes more limited. Timing of germination and wet weather is critical to effective control with this technique. Extremely moist conditions lengthen the treatment timing, but also can make it less efficient as the ambient moisture absorbs BTUs, requiring more to treat target plants. In contrast to what most practitioners have found, Ulloa et al. (2012) conclude that efficacy is actually higher later in the day when relative leaf water content is lower. Flaming under dryer conditions should always be weighed against the increased risk of fire.

3.2 Steaming

Lead author: Cheryl Wilen

Overview

Steaming and hot water are physical techniques of weed management where high temperature water is applied to damage plants through membrane rupture, protein denaturation, and enzyme deactivation resulting in leakage and loss of organelle function. High temperatures cause damage quickly while lower temperatures need more time. Plant parts exposed to temperatures as low as 113°F for extended periods of time can be killed.

Steam plus boiling water at about 221°F is applied using specialized equipment powered by diesel, gasoline, or electricity. Water is supplied either by a large tank attached to the machine or continuously through a hose. Another method uses much lower temperature water (~135°F), but the water is mixed with a biodegradable foam that insulates the application surface, allowing for longer heat retention. Damage to susceptible plants can be observed within minutes to 3 hours.

Both water and steam are applied through a wand-type applicator. The steam applicator uses a hooded spray head or shower head to dispense the mix of a saturated steam and boiling water. The foam machine's wand end is designed to distribute the foam quickly.

While these machines do not require extensive training to operate, they are labor intensive due to the time required to move hoses during the application and move the machine itself from site to site. Because treatment only kills plant tissue that is contacted, retreatment is usually necessary within 3 weeks in all but the coolest part of the year. At the time of this writing, costs of the machines (not including trailers and additional options) range from about $13,000 for the smallest steamer to over $40,000 for the largest foam system.

In general, grasses tend to be more tolerant of steaming and hot water treatmen than are broadleaf species. This is likely due to the ability of grasses to produce new growth from vegetative reproductive structures such as stolons and rhizomes or protected meristems rather than any special tolerance of the plant to high heat. Consequently, this technique is most effective on young annuals, especially dicots. More mature annuals will be suppressed or controlled but the labor and time needed will be increased. These techniques should not be considered effective for control but rather for local suppression of plants, since many species of plants, especially those larger than the 2-leaf stage, will regrow. Herbaceous perennials and perennial grasses can be suppressed but will regrow in as little as two weeks.

For both grasses and broadleaf plants, the thicker the leaves are the less injury that can be expected with steaming. Additionally, broadleaf species with wider leaves are injured more than those with narrower leaves.

How to Use

There is specialized equipment developed for steaming or hot water applications to weeds. Use of equipment developed for other uses, e.g., clothes steamers or boiling water in a pot is not recommended.

On hard surfaces and along fence lines, first cut down as much vegetation as possible using a string trimmer or other vegetation removal method.

Water temperature on the gauge for the saturated steam system should be 225-250°F. Adjust the pressure down to increase the temperature. The foam steam system has a lighted button that indicates when the appropriate temperature is reached.

For long hose distances (greater than 100 feet from an access point), it is helpful to have an assistant move the hose.

For saturated steam, the covered applicator head is placed over the weeds for a short time, generally less than 2 seconds and moved in a similar motion as if using an upright vacuum cleaner to cover an area. For larger weeds, the head can be used to knock the plant over and allowed to dwell on the plant for 5 to 10 seconds. Treated foliage will change color when the cells begin to leak. When using a "shower head" attachment, hold the opening about 8 to 12 inches above the plant and move it as you see the leaf color change to bright green.

For the hot water-foam system, the wand will expel foam and the operator should move quickly to make sure it is applied uniformly on the desired area. Foam application is much more rapid than saturated steam, but it is also less precise. It is important to follow the directions to ensure that the correct concentration of foaming additive is in the tank. Using the system to only apply hot water is not effective.

Either system can be used on herbaceous vegetation right up to the base of woody shrubs and trees without injuring them, though any leaves contacted may be injured slightly. Exposed roots should not be affected if they are mature and woody.

Efficacy depends on the amount of steam applied, the water temperature, the weed species, and the growth stage. Injury is rapid and often observed immediately after treatment. Maximum injury is usually observed at three days, but after this point most plants start to recover (at least partially).

Special Tips

If a plant has large leaves, make sure to contact parts directly under the top leaves which may be shielded.

For plants with tillers or lateral branching, the plant can continue to grow or recover even if all parts of the plant are thoroughly treated.

Most studies recommend that weeds should be controlled between the cotyledon and the two–true leaves stage. Otherwise, the effectiveness of the thermal treatment is reduced and an increase in fuel

consumption is required. Steam has been shown to be more effective on certain erect-growing broad-leaved weed species than on prostrate-growing weeds.

There is no evidence that weed seeds in the soil are killed by saturated steam or hot water treatment if the equipment is operated as recommended. If seeds on the soil surface are exposed to extended periods (30-60 seconds) of saturated steam, germination may be reduced. However, in practice, saturated steam is not applied to treated areas for that length of time.

Optimal Conditions for Use

Steaming and hot water can be used in nearly all types of sites if they can be applied safely. Equipment is heavy, so hoses must be long enough to reach the treatment area from a staging area where the equipment resides. As noted above, the system is most effective on young plants. It is ideal for treating newly emerged flushes of weeds.

Depending on the choice of equipment and availability of water to refill the tanks, one can expect to treat about 0.5-1 acre/day. Therefore, it is best suited for small areas and in special circumstances such as cracks and crevices around schools and other sensitive areas.

Steaming is fairly indiscriminate as a treatment tool but can be focused on small areas and is therefore moderately selective. The operator also has control over where to apply the steam or foam.

Treating at 3- or 4-week intervals appears to be the optimal time for weed suppression during periods of active growth. Waiting longer will make treatment more difficult by allowing the plant to recover more and a larger number of other germinating weeds to grow before treatment.

One study reported that plants were more sensitive (almost two times as sensitive) when treated in the late afternoon than in the morning.

Caveats

- Water and heat from the treatment may stimulate seed germination.
- During periods of active weed growth, expect to treat at 3-week intervals if suppression is to be maintained.
- It is often better to have two people work the area — one to hold the wand and the other to move the hoses.
- This is a very slow technique. It is probably faster than hand-weeding but slower than mowing or trimming. Expect to treat about 0.5-1 acre/day using one of the larger machines, factoring in the time needed to refill the water tank.
- A water source must be readily available to refill tanks or otherwise supply the machine, depending on the model.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. In general, these systems do not pose a hazard to operators, though operators should wear gloves and protective eyewear to protect from the hot hose fittings or in the event of a hose break.

Cultural resources. Low risk. This technique does not disturb the soil surface and poses no impact.

Habitat. Low risk. However, there is uncertainty about the environmental impact of the foaming additive, which is currently based on plant-based oils and may contain sugar, especially around water resources. As a precaution, it is best to stay away from waterways when using a foam system.

Sensitive species. Low-moderate risk. Noise may disrupt nesting birds and direct contact with foam or steam could harm ground-dwelling animals.

Erosion. Low risk.

Other Non-Chemical Methods to Combine With

Mowing large areas or string-trimming along fences, walls, and tree wells will reduce the time to apply the treatments. Efficacy will likely be increased for the foam system when upright growing plants are mowed as efficacy is improved the longer the foam can stay on the plant.

When Not to Use

Perennial plants, especially woody plants, will not be controlled with this technique. Plants with rhizomes, bulbs, and tubers will resprout if those organs have formed before the plant is treated. Plants with protected meristems tend to recover better than those with unprotected meristems.

These systems are about as loud as a gas-powered leaf blower so they may not be preferred in some areas where noise would impact animals.

There is uncertainty about the use of the foaming additive (currently plant-based oils, may contain sugar) around water.

Photographs

Left: Demonstration of steaming as a weed control tool. Photo credit: Claire F. Meyler. Right: Hot foam application. Photo credit: Cal-IPC.

Left: Transportation of portable steaming unit. Photo Credit, Jutta Burger. Right: Helpful signage for the public when using steaming to control weeds. Photo credit: Claire F. Meyler.

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Supplementary Information

None.

3.3 Girdling

Lead author: Shani Pynn

Co-authors: Pamela Beitz

Additional contributors: Ken Moore, Tom Reyes

Overview

Girdling is a technique that kills woody plants in place without cutting them down. It uses a sharp tool to cut through the bark of a woody plant in a strip all the way around the stem down to the wood. This severs the vascular cambium of the woody plant and cuts nutrient flow between the foliage and the roots. As a result, roots are starved of nutrients and the plant cannot grow more stems and foliage. Unless the plant can heal over the wound, it will die. If a plant has reproductive capacity to send up resprouts, it will recover.

Girdling is often used to control or eradicate large woody species where physical removal of woody biomass would be undesirable, unpopular, or cost prohibitive. Killing an undesirable tree in place by girdling also has the benefit of leaving standing snags for wildlife. Additionally, there is lower visual impact where the sudden removal of an entire stand would affect the areas aesthetics. Since die-off is gradual (taking months to years), the visual change in the area is slower. Killing mature trees slowly can also give replacement plantings time to grow, so more mature habitat is in place once treatment is complete. With some species, the shade produced by the dying trees can reduce the amount of suckering or other regeneration of the target species compared to techniques that remove biomass, thus opening the canopy and stimulating sucker growth.

Land managers may choose to use girdling when working in areas within public view, when raptors are using trees, when working in remote sites where other techniques are impractical, or when maintaining a density of trees or large shrubs is necessary to maintain a desired habitat type. This technique generally has a low impact on cultural resources, erosion, and surrounding habitat because it is highly selective and does not disturb soil. It is well-suited for remote sites because all tools needed for girdling can be carried by hand; it is also labor intensive and therefore inefficient for large stands of trees. When used alone, girdling is an effective control method for some species of mature woody plants, but not for very young plants. When combined with other techniques targeting seedlings and younger saplings, it can be part of a strategy to eradicate woody invaders.

How to Use

When used as a non-chemical control technique, girdling works by severing nutrient flow from aboveground portions of a woody plant to its roots and water flow from roots to leaves. It is only effective if the inner bark is completely severed around the circumference of a trunk and not allowed to regrow. A sharp tool is used to sever the outer and inner bark (cambium) around the entirety of all stems in either a ring (bark-ringing) or a series of overlapping cuts (frilling). This may be repeated in multiple sections, or the bark may be stripped to the ground (bark peeling). Girdling is most effective

when done just after a tree leafs out for the growing season, when it has used a maximum amount of its stored carbohydrates for new growth and well before it has begun to transition back into dormancy.

There are various ways of implementing this technique. One method is to use a chainsaw to cut three rings fully around the target trunk through the bark and cambium layer. Cuts should each be a few inches wide and a few inches apart. Another method is to cut and strip the bark in a 6- to 8-inch solid band around the trunk. This may require a chainsaw, hatchet, machete, etc. to cut through the bark at the edges of the peel area. Land managers frequently use these two girdling methods for Douglas fir and cultivars of Monterey pine growing in areas where they are not desired. Frilling is done by cutting overlapping slashes into the trunk at a downward/inward angle, cutting through into the wood and leaving a "frilly" appearance, hence the name.

The tools used for these techniques vary by target species and user comfort. For species with thin bark and younger growth, a sharp, strong hand tool such as a machete (used with caution) or hatchet (generally safer) can be used. Chainsaws are often the tool of choice for more mature trees with thick bark. All tools will need to cut through the bark layer and cambium down to the underlying wood. It is important to be familiar with the thickness of the bark and cambial layer in the species being treated prior to choosing a tool. Multiple tools may be effective, so tool choice may be dictated by safety and ease of use. Low branches may need to be trimmed to be able to access the main trunk of a tree or shrub for girdling. If a tree or shrub is multi-trunked, all main stems will need to be girdled.

As each tree is treated individually, this technique is highly selective. Non-target damage is only expected if the non-target species is growing close enough to the target that it impedes maneuverability around the target trees/shrubs with the cutting tools. In this case, non-target damage may include broken branches and vines.

Girdling can be effective any time of year but is expected to be more effective when the target species is preparing to go into dormancy at the end of the growing season (leaves still green). Because girdling prevents nutrients from traveling down into the roots, it is most effective after the plant has utilized carbohydrate reserves in roots for growth in the spring and before it sends reserves back down to roots in the fall. If done too early (new leaves still flushing or at the beginning of a long growing season), the plant may be able to heal in time to replenish carbohydrates. If done nearing leaf drop, the plants may already have enough nutrient stores to survive dormancy, heal, and regrow.

Special Tips

Cutting multiple bands of bark rings or frills or making the bands thicker (from a few to 12+ inches), can help to prevent regrowth of bark when dealing with trees with lots of knots in the trunk.

Revisiting the treatment site is recommended to ensure that the cambium has not regrown across the cuts, especially with Eucalyptus and other resprouting woody species. Resprouts will need to be cut repeatedly to fully exhaust energy stored in the roots.

Some practitioners have experimented with covering and sealing girdle cuts with black plastic to prevent resprouts. This technique may be useful in remote areas where treated trees cannot be checked frequently, though tarping also requires regular maintenance. Some species, like tree-of-heaven, can send up sprouts from roots some distance from the main stem.

Optimal Conditions for Use

Girdling is most effective on species that do not resprout, in drier site conditions, and when applied before plants begin to store nutrients for dormancy. It is most effective on mature trees, older brooms, and other mature shrub species. Non-resprouting conifers, and some tree species that resprout from lignotubers rather than lateral roots are especially susceptible to girdling. Trees in open landscapes, such as grasslands, are easier to access for girdling and to track after treatment.

Caveats

This technique should only be used where standing dead trees and the associated risks — for instance, falling branches — can be tolerated. It should also not be used in areas where eradication is the immediate management objective because a girdled tree can take months to years to die, during which time it can still produce viable seeds and other reproductive structures.

When cutting, pay special attention to any undulations in the trunk shape as the cambium will undulate as well and may be difficult to sever completely.

Girdling may be less effective under wet conditions where plants have a greater chance of resprouting. It is also less effective for younger, vigorous trees and shrubs that can more easily regrow.

Girdling (without supplemental herbicide treatment) is generally not recommended for eucalyptus, tree-of-heaven and other woody species which can resprout prolifically.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety: Moderate. Hazards include cutting risk by workers using sharp hand tools and chainsaws. Hazards of these tools differ based on many factors including familiarity with the tool used, target species, field conditions, etc. Generally, chainsaws are more hazardous than machetes, which are more hazardous than hatchets. Maintain a suitable safe distance between workers, and ensure they have any PPE associated with the chosen work tools. Ensure workers are trained to use these tools safely in relation to the individual environmental hazards of the work site. Be aware of and address tree deadfall risks after girdling.

Cultural resources: Low. Girdling does not impact surface and subsurface cultural resources.

Habitat: Low. There is little concern of hazards to nontarget species or the environment because of the high specificity of this technique. Over time, the treated vegetation may pose a falling hazard after they die. The technique therefore holds a delayed potential for environmental hazards and long-term loss of nesting habitat. This technique can also increase fuel loads, especially in the canopy. Treatments should be timed and spaced to prevent accumulation of fuels in case of a wildfire. This is likely a short-term risk as fine fuels will fall off the tree relatively quickly after tree death. These hazards can both be reduced by removing the biomass of dead individuals after treatment takes effect. Removal of this kind often comes with a high cost.

Sensitive species: Low. Be aware and mitigate as needed for changes in raptor perch and nesting opportunities long-term.

Erosion: Low. There is no ground disturbance. In the long-term, other vegetation will need to establish to hold soil in place.

Other Non-Chemical Methods to Combine With

Girdling may be an effective addition to tarping a cut stump of a resprouting species. For this, the cut stump should be girdled below ground level before tarping to reduce resprouting. Bark peeling can also reduce regrowth of cut stumps. Use of this combination of techniques requires extensive effort, first to fell the tree, then to dig an adequately sized hole, and finally to implement the girdle band below the soil surface.

Girdling may be combined with competitive planting of desirable species. Smaller invasive plants can be removed using a variety of other tools and approaches.

When Not to Use

This technique is ineffective on seedlings and saplings, palm trees, species with undulating bark, and species with the ability to resprout from roots. For resprouting species, such as eucalyptus, black locust (*Robinia pseudoacacia*), or tree-of-heaven (*Ailanthus altissima*), girdling may actually increase the cover of a problem tree by triggering heavy resprouting. Do not use this technique on these species. Girdling is difficult on multi-trunked trees and shrubs like castor bean (*Ricinus communis*).

Photographs

Chisel girdling. Photo credit: E. Thomas Smiley, Bartlett Tree Experts.

Girdled trees. Left: A dead standing Norway maple girdled by chainsaw. Photo credit: Geoffrey Kempter. Right: Norway maple resprouting after unsuccessful girdle. Photo credit: E. Thomas Smiley, Bartlett Tree Experts.

Left: Wide girdle. Photo credit: Dane Jenson. Right: Inspecting progress on a triple girdle (girdles to be completed). Photo credit: Cal-IPC.

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Supplementary Information

None currently

4.Covering Plants with Sheet Barriers

Covering Plants with sheet barriers includes techniques that provide a surface covering designed to kill existing vegetation under it and/or to eliminate the seed bank of an undesirable plant. The techniques covered are:

- Mulching.
- Tarping.
- Solarizing.

4.1 Mulching

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Overview

Mulch is "a protective covering… spread or left on the ground to reduce evaporation, maintain even soil temperature, prevent erosion, control weeds, enrich the soil, or keep fruit (such as strawberries) clean." (Merriam-Webster dictionary). In the context of non-chemical weed management, mulches are generally derived from fresh or composted plant materials such as wood chips or bark but can also be other materials including straw, paper, nut shells, rice hulls, or other readily available material. Inorganic mulches include gravel and polypropylene cloth.

Sheet mulching is an alternative method of covering soil with a solid material such as cardboard, typically combined with layers of degradable mulch above and below. In addition to controlling annual plants, this method is used to suppress and sometimes control perennial plants including some hard-to-manage rhizomatous plants.

Disturbed sites where weeds are plentiful and native plant cover is low are excellent candidates for mulching. Mulch can be applied any time of the year and in most kinds of sites. Where it can be applied easily and economically, mulch provides excellent short- to mid-term (weeks to months) suppression of annual weeds. Control can be extended if the mulch is replenished to the depth required to suppress weed germination and growth. Mulch needs to be reapplied regularly to maintain an effective depth; therefore, it is usually not used for long-term control.

There are limitations related to scale, plant form, landscape characteristics, and application that may prevent this technique from being used in some situations. Mulch is heavy and bulky, making it difficult to move to remote sites. It is also best used at small scale (less than 1 acre) or for specific uses such as in the planting basin for new plantings. It is important to remember not to push mulch directly up to base of desirable plants to avoid creating an environment for moisture loving pests such as pathogenic fungi. Conversely, mulch applied correctly has been shown to reduce root rot in some tree species.

The cost of mulching is moderate to moderately high. Input costs include the mulch itself, trucks to carry the mulch (to cover 1000 ft^2 to a depth of 4 inches requires about 13 cu yards, which is about the volume of a large commercial dump truck), a crew to spread, follow-up hand weeding, and replenishment. Mulch can be spread using a manure spreader or from a truck mounted mulch blower. The latter method allows for covering a large area and it can be applied more precisely than the manure spreader. Sheet mulching requires the additional cost of sheet material and labor.

How to Use

Mulch can be applied to any level or slightly sloped area. It is a very effective choice on bare, accessible, disturbed areas. Steep slopes are usually not a good choice as mulch can move with water flow, wind,

and after heavy rain or irrigation. It can be used in most locations except areas adjacent to water bodies for similar reasons.

Mulch should be free of weed seeds and plant diseases. Avoid using stockpiled chips as they may harbor pests. Where possible, use locally sourced mulch rather than bringing mulch from elsewhere. Chipping fallen or cut trees on site as a mulch is highly effective in isolated areas such as those in restoration. Even *Arundo* mulched using a tub grinder on site has been useful as mulch to prevent annual plant establishment. This mulch was used in upland, not riparian areas. Despite popular belief, eucalyptus wood chips also make a good mulch and will not negatively affect the growth of established plants. If chipping trees to use as a mulch in place, be aware that seeds of non-native plants may be spread in the process.

While a range of mulch sizes are desired in most cases so that they pack together and reduce spaces for weeds to pop through, the smaller the mulch pieces, the less the depth required. A mix of bark or wood chip sizes that are roughly ½ inch to 2 inches will suppress weeds and not break down too quickly. A 4-inch depth is usually what is needed for weed suppression when sites can be checked regularly, but 6 to 8 inches can be applied on sites that are not maintained regularly.

Alternative mulch materials or techniques such as weed free rice straw installed 3 inches deep have been used successfully for control of *Ehrharta spp.* (Grass and coastal sage scrub species were successfully seeded over the mulched area.) Burlap sacks can also be layered (pseudo-tarping) and then covered with mulch.

Sheet mulching is a specialized technique where a solid but biodegradable material such as cardboard is layered and covered with mulch. Additional layers of organic material can be added to increase microbial activity and enhance soil. An example is a layer of rice straw, covered with sheets of cardboard, covered with another layer of rice straw, and finally a top layer of wood-based mulch.

Sheet mulching is best on areas less than 1000 ft^2 due to the amount of material inputs and labor required. However, it is not effective on areas that are too small, where there is a high perimeter to area ratio. Many vegetatively reproducing plants growing in patches less than 1000 ft^2 can be effectively suppressed using this technique.

Cardboard decomposes quickly, so transplanting into it is easy. However, prior to planting, do not put stakes in the cardboard or otherwise puncture the cardboard barrier. Avoid wetting the sheet mulched area as that encourages it to break down faster.

Below are step-by-step instructions for conventional and sheet mulching techniques:

Conventional Mulching

- Cut all aboveground biomass except desirable vegetation.
- Remove thatch to ensure good soil contact and no protruding vegetation.
- Ensure equipment and mulch does not have other pests (weeds, pathogens, insects).
- Spread mulch 6 to 8 inches deep.
- Monitor mulch depth over time to maintain 4 inches.
- Complement mulching with hand weeding and adding chips as needed.

Sheet Mulching

- Prepare the area by cutting down existing vegetation by mowing or using a weed whip.
- Apply a base layer of 2 to 3 inches of straw, leaf mulch, or other organic material (optional).
- Cover with cardboard, being sure to overlap edges to avoid cracks.
- Cover cardboard with straw, leaf mulch, or other organic material. This layer should be about 5 inches deep if compressed but more if loosely stacked (optional).
- Completely cover with wood chips (4 to 6 inches). A little leaf material may be included in the top layer.

Special Tips

Placing mulch around desirable plants may be difficult if the plants are small or have low foliage. Mulch should not be directly against a tree trunk. Nevertheless, unmulched areas around the tree or other plant will be a place where weeds can establish.

Optimal Conditions for Use

Relatively open and level areas that are accessible by vehicles. Gently sloping sites are also suitable if precautions are taken to reduce movement of the mulch during rain or supplemental irrigations. Mulch should be used as a short-term (1 to 6 months) to medium-term (6 to 24 months) method to manage weeds in large areas until a longer-term solution is in place.

Caveats

Gophers may burrow under mulch. This is more of a problem in sheet mulching where the gophers can tear holes in the cardboard.

Mulching is non-discriminate. Native plant seeds in the soil will also be suppressed.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. A particle mask, eye protection, and gloves are recommended to reduce exposure to dust and fungal spores present in mulch.

Cultural resources. Low risk. This technique may even help to protect cultural sites.

Habitat. Low-moderate risk. Mulch will fundamentally change the ground that it is applied to by reducing light penetration to the soil surface, increasing surface soil organic matter content, and increasing site surface water retention. Be aware of whether these effects are desirable or not. Mulch may crowd out desirable vegetation that many species are dependent on. If mulch is very thick, it may be a fire risk under dry conditions. Keep mulch away from flammable structures. Pine needle mulch is especially combustible.

Sensitive species. Low-moderate risk. Mulching may create habitat for some species by providing cover and nesting material. It may also create habitat for species that are not desirable at a site, or may

degrade habitat by eliminating exposed bare ground, associated soil crusts, and nesting sites for some ground-dwelling species.

Erosion. Low risk. This technique reduces soil erosion, however, mulch itself may move offsite with heavy rain, wind, or irrigation.

Other Non-Chemical Methods to Combine With

Mowing, shallow cultivation, weed whipping, or any other mechanical method that reduces resident vegetation prior to mulching will improve the efficacy of this technique. Manual removal with hand tools can supplement mulching by removing the few weeds that may emerge through mulch.

When Not to Use

Perennial plants are rarely controlled by mulch alone. Sheet mulching may be effective for some rhizomatous plants, but bermudagrass and bindweed are a couple of the more difficult weeds to control with sheet mulching because they will continue to grow upwards and tend to exploit any seams in the sheets, even when overlapped.

Mulch should not be used where at least monthly check and maintenance cannot be done. It should not be used where there is the likelihood of it being moved, either intentionally, such as for planting, or unintentionally, such as through water or wind.

Photographs

Sequence of lawn removal, application of sheet mulch and wood chips, and installation of new plants. Photo credit: Kimberly Crispin.

Sheet mulching sequence to create a bioswale. Photo credits: Kimberly Crispin.

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Supplementary Information

None

4.2 Tarping

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Overview

Tarping involves using heavy plastic, polypropylene, or other light-blocking material to cover the ground to prevent weed growth. Tarps can also be used to cover tree stumps to prevent resprouting. Tarps are usually durable enough that they can be stored and reused multiple times. Because tarps must be left in place for several months to be effective, this method is most practical for small areas and to stop an isolated infestation or to contain a part of a localized weed patch to prevent expansion while the rest is treated.

Tarps placed on the ground will suppress plant growth by both blocking light, which is required for growth, and by stimulating (some) seed germination, by maintaining moist conditions. When the seeds emerge from the soil, they quickly die due to the lack of light, thereby reducing the population in the soil seed bank. Surface tarps are left in place for weeks to months to even years, depending on the species being treated and its ability to regrow.

Tarps can also be used to reduce the effect of resprouting from cut stumps by blocking light to the newly sprouted buds or controlling sprouting from rhizomes, stolons, bulbs, and other vegetative propagules. Tarps used for this purpose cover a much smaller area such as only the stump or small planting bed and are also left in place for months to years.

How to Use

Tarping is most effective if the target area is exposed to full sunlight. For best results, use 6mil UV protected black plastic or black or brown plastic tarps with grommets.

For seed bank reduction: Mow the area as low as possible to provide an even surface to lay the tarp. Where permissible, till the site to be able to lay the tarp flat. Cover site with tarp and hold in place with sandbags, rocks, filled erosion socks, duck-billed anchors, U-nails, or other fasteners. Leave on for 3 to 6 months during the period of germination for the plants of concern. Remove tarp and plant desirable species into the area, minimizing soil disturbance so as not to move any weed seeds to the surface.

For treating perennial plants: Cut or mow plants to a height of less than 6 to 8 inches. Cover area with tarp and hold in place with sandbags, rocks, filled erosion socks, duck-billed anchors, U-nails, or other fasteners. Tarps must extend well beyond the perimeter of the patch being treated, farther than where plants will send out lateral shoots (ideally greater than 6 feet). Monitor for runners that may emerge along edges. Depending on species, the tarp may be removed in 6 months for many herbaceous species to 2 or more years for plants with resprouting roots, deeper rhizomes, or seasonal resprouting. Monitor and hand remove any new sprouts. See Supplemental Information for specific instructions on tarping *Arundo* and pampas grass.

For treating stumps: Cut stump low and level to the ground and clear a space around the stump to be tarped. It may be helpful to dig a trench around the stump to facilitate tarp placement. For trees that

are prone to sprouting, 3 layers of 6mil tarp can be used. See Supplemental Information section for specific instructions on tarping *Eucalyptus* stumps and *Acacia*.

Spread tarp and anchor around edges with U-nails and/or duck-billed anchors. Some practitioners tie the tarp on the tree stump. Avoid holes in tarp. Extend the tarp far enough beyond target so that sprouts, runners, etc. will not emerge past the tarp. If possible, cover with chips or other plant material. Check regularly to ensure that the tarp is still in place and intact. Allow the tarp to remain in place for several years.

Special Tips

On rocky slopes, wet areas, uneven ground, or ground with large amount of duff, use longer staples or anchors (at least 12 inches).

Commercial plastic tarps are expensive but do not degrade. Permeable weed cloth, in contrast, will deteriorate too quickly, even if installed in two layers.

Tarps must be patched if damaged or else light will get through, and the weeds will continue to grow. While duct tape can be used, tape that is specific for tarps will provide a longer-term repair, is UV resistant, waterproof, and bonds better than duct tape.

Optimal Conditions for Use

Tarping works best on smooth, flat areas with highly isolated plants or patches generally less than 40ft^2. This can also be effective on a large area with many isolated patches. It also works best on tree stumps if they are cut low and level to (ideally below) the ground.

Caveats

- This technique is non-selective. It will kill all plants it covers.
- It takes time — often a year or more of tarping — to see good results.
- Tarps must be checked regularly for holes and to make sure they are secured.
- Tarping in public areas may result in tarps being damaged or stolen.
- Tarps draw attention and may be perceived as trash that should be removed. Add signage to limit curiosity.
- Long-term tarping, e.g., 1 year or more, has unknown effects on local soil biota.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. Best practices should be used when using tools to install tarps to avoid injury. Tripping could be a problem, so it is not recommended to use over trails or in areas of high foot traffic.

Cultural resources. Low risk. Digging around stumps to secure tarps could impact buried resources if they are directly on site.

Habitat. Low risk. This technique is typically used for small contiguous patches of single species or stumps. Tarping should be removed from site after use.

Sensitive species. Low risk. Immobile species e.g., plants and some soil dwellers may be impacted. Species trapped under plastic e.g., snails, lizards will be impacted. Do not use tarps over sensitive plants or in areas where sensitive animals have been documented. Tarps will kill almost everything under them.

Erosion. Low risk. Tarps will protect sites and will minimize soil disturbance. However, if a tarp is on a slope, the unprotected areas down slope from the tarped area will be susceptible to erosion. Bare areas exposed after tarping will be vulnerable to erosion.

Other Non-Chemical Methods to Combine With

Tarping applied in combination with a mow-and-till treatment was effective at controlling perennial pepperweed. Mow–Till–Tarp treatment is extremely time consuming and has the potential to limit native plant community recovery.

When Not to Use

Avoid tarping large (>0.01ac) areas and areas where the tarps may be disturbed. This technique is probably not a first choice for prolonged, continuous coverage of large areas, due to the associated destruction of habitat and soil organisms.

Photographs

Tarping with volunteers. Left: Tarping to control *Calystegia sepium* and roots of *Rubus ulmifolius*. Right: Wood chips and mulch added to hide tarps controlling *Calystegia sepium* and roots of *Rubus ulmifolius*. Photo credit: Susan Schwartz.

Larger-surface and long-term tarping. Left: Tarps installed long-term (5 yr) to control *Calystegium sepium*. Photo credit: Susan Schwartz. Right: Large-scale tarping for spotted knapweed (*Centaurea stoebe*) at the Klamath National Forest. Photo credit: Erin Lonergan.

Tarping to prevent resprouting of Bluegum eucalyptus cut stumps. Photo credit: HortScience Bartlett Consulting.

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Supplementary Information

The following materials have been used successfully by practitioners for specific weed issues:

- Thick tarp (e.g., Merafi 800) is good for perennial woody species with complex root structure if herbicide not an option. It has been used effectively on *Spartina* as well.
- Biotelo is a tarp material that allows no light penetration and is biodegradable. It has worked on pampas grass and *Arundo* and was installed after winter rains. Plants were killed after 6 months.
- A standard brown tarp w grommet holes, covered with duff, has worked in public areas for pepperweed and *Calystegia sepium*.

Below are tarping tips for specific weed species:

Acacia

1. Dig trench around plot 2 feet from nearest stump and 1 foot below grade.
2. Cut to within 12 inches of grade (lower is better).
3. Tarp stumps with 3 layers of 6 mm black plastic.
4. Backfill trench.
   Notes: Tarps can be covered with duff. Tarps may not hold in place on steep hillsides.

Pampas grass (*Cortederia* sp.)

1. Cut off stalks and leaves as low and flat to the ground as possible.
2. Cut off seed part of stalks and dispose of safely.
3. Cover plants with biodegradable tarps.
4. Secure the tarp over the clump with staples, washer pins, or rocks or other heavy objects from the site. Staples are more appropriate for non-rocky soils and should be pounded in with a dead blow hammer about every 2 feet around the perimeter or closer if needed. More rocky ground may require washer pins and a 3-lb sledgehammer, applied at the same spacing.
5. Pile all the stalks and leaves on top of the plants to keep tarps in place and to obscure from view by passersby.

Arundo

From: Center for Ecological Restoration and Stewardship Circuit Rider Productions, Inc. (2007).

1. **Cut** the stalks to a standard height as close to the ground as possible. Make sure that the cuts are level, not angled. Stalks cut at an angle could cause serious injury if a fall occurs and may poke

holes in the tarp. If the site can be cleaned up to make the tarp installation easier, do so — remove brush, litter, or any object that may interfere with the tarp laying flat.

2. **Measure** the longest width by the longest length of the clump and add about 10% or 4 feet, whichever is smaller.

3. **Cut** the tarp to this measurement. Use tarp pieces as large as possible to minimize any "quilting effect" — *Arundo* growing between tarp edges. The tarping material often comes in 12-foot rolls, so for larger clumps, some overlapping of pieces may be necessary. Keep in mind that larger tarps are easier to reuse because they can be cut smaller if necessary.

4. **Secure** the tarp over the clump footprint with staples, washer pins, or rocks or other heavy objects. Staples are more appropriate for non-rocky soils and should be pounded in with a dead blow hammer about every 2 feet around the perimeter, or closer if needed. More rocky ground may require washer pins and a 3-lb sledgehammer, applied at the same spacing. Sometimes rocks or deadwood can be used to secure the tarp, but do not mine the surroundings. Use these materials only if the other methods are not working and use them sparingly.

5. **Monitor** the tarp every two weeks, patching any holes that occur. Avoid walking over the tarps as much as possible. Even a very small hole can provide enough light for the *Arundo* to survive.

6. **Timing** is crucial to the effectiveness of tarping. Tarps should be laid during the active growing season and when there is minimal risk of being dislodged by floodwaters. In the Russian River watershed, the time period stipulated is May 1 through October 31, unless installed safely outside of the flood area. Tarps must remain in place at least six months to be effective, and often need to be reapplied the following season to allow for complete kill. The area should be monitored for at least an additional growing season after the tarp has been removed to ensure the root mass will not resprout.

Materials for tarping *Arundo*:

- Tarping material. Choose a plastic material that is completely impermeable to light, as even a small amount of light can allow the root mass to survive. Hold a sample up to a bright light to verify. The material should also be of sufficient strength to keep resprouting stalks from poking through. A tensile strength of 200 lbs has proven sufficient. Finally, the material should be sufficiently pliable and lightweight to be easy to use (usually a thickness of 12 mil).
- Tape measure.
- Cutting implement.
- Staples (12-inch, 9-gauge) staples for non-rocky ground.
- Washer pins (12-inch, 7-gauge) for cobble or other rocky areas. These are headless nails with a bulge at the top and a washer attached below the bulge.
- Dead blow hammer (with staples) or 3-lb. sledgehammer (with washer pins).
- Proper protective clothing: long pants and long sleeves, eye protection, gloves, and boots.

***Eucalyptus* stumps**

1. For large diameter *Eucalyptus* trees, cut 4 to 6 inches from the ground with the cuts angled to match the lands contours.
    a. For small diameter trees (up to 6 inches in diameter), cut as close to the ground as possible for either tarping or removal with a weed wrench.

2. Clear duff away from around the stump and create a small trench around it.

3. Cut the tarping material, adding about 10% to the longest width by the longest length of the stump or clump of stumps (if covering more than 1 stump at a time).

4. Secure the tarp over the stump or around the clump footprint with staples, washer pins, or rocks or other heavy objects. Staples are more appropriate for non-rocky soils and should be pounded in with a dead blow hammer about every 2 feet around the perimeter, or closer if needed. More rocky ground may require washer pins and a 3-lb sledgehammer, applied at the same spacing. Rocks or deadwood can be used to secure the tarp but use these materials only if the other methods are not working and use them sparingly.

5. Cover the stump or clump with chips or other onsite organic debris.

6. Avoid walking over the tarps and monitor them regularly. Tarps must remain in place at least 6 months to be effective and may need to be reapplied the following season to allow for complete kill. The area should be monitored for at least an additional growing season after the tarp has been removed to ensure the root mass is not resprouting.

   Materials for tarping *Eucalyptus*:
   - Tarping material: black plastic.
   - Tape measure; cutting implement; staples (12-inch, 9-gauge) staples for non-rocky ground; washer pins (12-inch, 7-gauge) for cobble or other rocky areas; dead blow hammer (with staples) or 3-lb. sledgehammer (with washer pins).
   - Proper protective clothing: long pants and long sleeves, eye protection, gloves, and boots.

4.3 Solarizing

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Overview

Soil solarization is a hydrothermal method (combining moisture and heat) for controlling weeds by using plastic sheeting to capture radiant energy from the sun. Solarization is a simple method appropriate for open sites where the plastic can be undisturbed for the 4- to 6-week solarization period. Solarization is most effective in warm, sunny locations such as the Central Valley, desert valleys, and other inland areas of California. It has also been used successfully in the cooler coastal areas of California during periods of high temperature and no fog. Solarization differs from tarping in that the goal of the treatment is to heat the soil to a temperature that is lethal to the target pest(s) whereas the mechanism of control using tarping is light exclusion and physical suppression of the emerging seeds or sprouts.

Soil moisture is important in this process since wet soil conducts heat better than dry soil. Moisture also stimulates germination, making seedlings more vulnerable to the heat.

Because an area must be fully covered by plastic sheets, it is best suited to areas of less than 1 acre, and optimally less than 0.1 acre, in relatively even areas. Additionally, arrangements must be made for the removal and disposal of the plastic.

The effect of solarization is greatest at the soil surface and decreases at deeper soil depths. The maximum temperature of soil solarized in the field is usually from 108° to 140°F at a depth of 2 inches and from 90° to 99°F at 18 inches. Control of weeds is usually best for those found in the upper 6 inches of soil. Solarization generally does not control perennial weeds since perennials often have deeply buried underground vegetative structures such as roots, corms, tubers, and rhizomes that may resprout.

How to Use

The procedure must be conducted during the hottest time of the year to ensure that very high soil temperatures are achieved. For most of the state, that is in late summer but in parts of desert and Central Valley regions, solarization can be done from late spring to early fall.

In general, transparent, or clear plastic is most effective for solarization, as the heating rays from the sun will pass through the sheet and be trapped to heat the soil below. Sunlight will also stimulate germination of many weed seeds that are at or near the soil surface. Usually, black plastic is less effective because it absorbs and deflects part of the heat, rather than trapping as clear plastic does. However, in cooler or coastal areas, black plastic is sometimes better than clear because weeds will not grow beneath it, as they will under clear plastic when temperatures under the plastic are too low to kill them. In this case, the black plastic should be left in place for several weeks during the hottest part of the year and falls under the control method of tarping. (See Tarping BMPs).

Several thicknesses of plastic material are available. Thickness is measured in ‘mils’; 1 mil = 0.001 inch (0.025 mm). Consider the following factors when deciding on the appropriate thickness to use:

- Thinner gauges of plastic (3 mil or less) convey heat more effectively than thicker gauges. Very thin plastic (1 mil) provides greater heating but is also more susceptible to tearing from wind or animals walking on it.
- Slightly thicker plastic (1.5 to 2 mil) is better in windy areas.
- Thicker plastic (4 mil or more) can be used if the treated area is small.

Plastics designed for large-scale solarization are usually treated with an ultraviolet (UV) inhibitor so they will not break down quickly in sunlight. These are usually supplied in 4-foot to 12-foot-wide rolls, often 1,000 feet long.

Plastic sheets without UV protection should be watched closely so they can be removed before deteriorating to the point where removal and disposal are difficult. If a longer solarization period is desired, small areas can be covered again with fresh plastic. Any holes or tears should be patched with durable patching tape.

Double layering plastic in cooler or smaller locations may be helpful as it could gain an additional 2° to 10°F over that obtained with a single layer. In this case, a small layer of air between the layers of plastic is needed. This can be achieved by placing a PVC pipe between the two layers.

There are generally five steps to solarizing soil:

1. Make the area to be covered as smooth and flat as possible. Raking or cultivation before installation of solarizing plastic may increase seed germination which will increase the effectiveness of the treatment, and a smooth bed will allow the plastic to lie snugly against the soil, producing fewer air pockets. Air pockets between the plastic reduce soil heating and are also more likely to result in the plastic flapping and tearing in the wind.

2. Irrigate the soil. Because solarization is a hydrothermal process, if the soil is not moist, the effect of solarization will be reduced considerably. In all but high clay soils, best results are obtained if the soil is wet to saturation or at least a wetted down to couple of inches past where the majority of the weed seeds or vegetative propagules are. This is because the area must stay as moist as possible for the entire treatment period. Soils with a high amount of clay should be moist but not overly wet.

3. *Install plastic tarp.* Install the plastic tarps to cover the site as soon as possible after the water has been applied to reduce evaporation. Unless the soil gets dry during soil solarization, do not irrigate again, as this will lower the soil temperature and lengthen the time required for successful solarization. The plastic must be held as tightly as possible against the soil. One way to hold it down is to dig a trench 4 to 6 inches deep around the perimeter of the area that is going to be solarized. Lay the plastic out over the area with one edge in the trench. Cover that edge with soil to hold it down. Pull the plastic tight from the other side and bury that edge in the corresponding trench. Do the same with the other sides and then walk around the perimeter of the trenched area to pack the soil down around the edges of the plastic. It may also be helpful to add bricks or other weights around the edges to hold the plastic in place. The closer to the soil surface the plastic is, the better the heating.

4. Maintain solarizing temperature. The cooler the soil temperatures, the longer the plastic needs to remain in place to raise the temperature to desired levels. The goal is to maintain daily maximum temperatures in the top 6 inches of soil to 110° to 125°F. You can use a soil thermometer or temperature probe to check. Check the plastic tarps frequently and repair any tears that develop. About six weeks of soil heating during the warmest time of the year is usually sufficient to control most susceptible weeds.

In cool, windy, or cloudy locations, it may be necessary to leave plastic in place up to 8 weeks. Conversely, during very hot weather in the warmer parts of the state, the plastic may only need to be in place for 4 weeks.

5. Remove plastic. After solarization, the plastic must be removed. When doing so, take care not to disturb the underlying soil which can bring up viable weed seeds from untreated edges and furrows or from deep layers that did not reach lethal temperatures. The area should be planted immediately with seeds or transplants. Delaying revegetation may invite weed colonization from outside sources.

Optimal Conditions for Use

Optimal conditions include hot temperatures, no shade or canopy cover, a level or south-facing site, well-moistened soil, and a mowed, bare, or cultivated soil surface. Soil should be flat with few clods so that the plastic is right on the soil surface. This can be done by dragging a chain-link fence piece or thick piece of lumber across the area prior to soil wetting.

Soil should be thoroughly wetted. If natural rainfall is not sufficient, supplemental irrigation is required. Sufficient rainfall may not overlap suitable high temperatures in all areas of the state.

Because solarization is most effective in the hottest time of the year (late summer for most of California), seeds that would be germinating in the fall and winter are controlled best. Because seeds that are in the top 4 inches are the primary target of this method, it is imperative that the soil is not disturbed so that seeds deeper in the soil profile are not brought to the surface where they can germinate.

Caveats

- Not effective on dry soil. A water truck or other water supply source is needed to pre-irrigate. May need a long hose and pump for sites that are farther from the road. In desert areas, where the temperature is expected to be high even in the spring, but water is limited, plastic can be applied soon after later season rains, but the plastic may need to remain in place for a longer period of time.
- Can be effective on all but north-facing slopes, but is most effective where solar angle is maximized, e.g., flat, or south-facing slopes.
- Due to the weight of the plastic rolls and the need for pre-irrigation, the site should be relatively accessible by vehicles (no more than 300 feet from a roadside is recommended).
- Plastic must be intact — any holes from animals walking across or edges being lifted by wind must be repaired immediately.
- Trenching the site perimeter to secure the plastic material is typically the most difficult and time-consuming step.
- Soil texture is important. In rocky sites, it will be difficult to place the plastic close to the soil surface. Additionally, trenching for burying the edges can be difficult. In those cases, the edges can be lined with bricks for small areas.
- If the desirable plants are perennial, there is a better opportunity for solarization to control the weeds and have less impact on wanted populations. If the desirable plants are annuals, they would likely be impacted. It is also easier to apply the plastic if there are larger patches of weeds and fewer desirable plants to work around.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. Because of high heat generated, the operator should be aware of chance of minor burns while patching plastic tarps. Rolls of plastic are very heavy and may need equipment or multiple people to carry or install.

Cultural resources. Low-moderate risk. Trenching to install the plastic may disturb some sites. Be aware that permits may be needed if cultural resources are near trenching areas.

Habitat. Low risk. This technique is typically used on highly degraded sites as this is a non-selective method for suppressing or killing plants. Plastic should be removed and disposed of after use.

Sensitive species. Low-moderate risk. Immobile species such as plants and some soil dwellers will be impacted. Species trapped under plastic such as snails, lizards, small burrowing mammals will be impacted and may be killed.

Erosion. Low risk. Plastic sheets will protect sites from erosion during solarization, however bare exposed ground will be vulnerable to increased erosion after sheets are removed. If the plastic is on a slope and rainfall occurs, areas that are immediately downslope will receive extra runoff and could be susceptible to extra erosion.

Other Non-Chemical Methods to Combine With

Cultivation and smoothing the soil surface prior to applying plastic will allow the plastic to be placed with little air between it and the soil surface. It will also bring buried weed seeds to the surface where they will be exposed to higher heat. Low mowing will suffice if cultivation is not possible. Biomass should be removed after mowing to ensure the plastic can be installed close to the soil. Competitive planting can be used to revegetate bare ground once tarps are removed.

When Not to Use

This technique is not effective at sites that are shady or otherwise do not get full sun, sites that are rocky such that plastic does not have direct soil contact, and sites with burrowing animals (e.g., pocket gophers) that can tear plastic. This technique is not effective for controlling perennial plants, hard-seeded plants such as clovers, or *Malva* species which appear to tolerate solarization.

Other methods should be used when restoration overlaps with time needed to solarize (generally 4 to 6 weeks in summer). Planting should be done as soon as possible after the plastic is removed. Do not use solarization in a relatively intact native habitat since it is not selective and will kill desirable plants.

Photographs

Solarization sequence in City of Irvine Open Space Preserve. Left: Digging trenches for plastic with a backhoe. Center: Site prep after mowing and before installing plastic. Right: Freshly installed solarizing bed. Photo credit: Robert Freese.

Soil solarization sequence in Bommer Canyon, Orange County. Left: Year 1 (2018). Center: Year 2, first year after seeding with natives (2019). Right: Year 3, second year after seeding (2020). Photo credit: Robert Freese.

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Supplementary Information

Black plastic is also a good tool for deactivating seed and vegetative propagules at remote sites. Removed seed heads and vegetative material accumulated after pulling is placed in black plastic bags and left in the sun. Plant debris can get above 140 degrees in the bag. See "Invasive weeds in remote locations can be killed with solar tents" https://ucanr.edu/sites/Solarization/Natural_resources_users/Weed_solarization/

5.Controlling Plants at a Plant Community Scale

Techniques in this section manipulate more than just the target species they are intended for. They affect ecological process that in turn may provide long-term benefits to a plant community while also helping to control a target weed. Techniques in this section include:

- Competitive Planting.
- Burning.
- Grazing.
- Mechanized Tillage.

5.1 Competitive Planting

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Overview

In competitive planting, native plants or otherwise desirable plant species are planted to prevent the spread of weeds or to directly compete against weeds and reduce their population. The effectiveness of this technique relies on the match, or sometimes the mismatch, in resource use (usually light or water) between the weed and desirable competitive plants. It also depends on the ability to initially reduce competition from weeds enough for the outplanted species to get established.

Success of this technique depends upon correctly choosing plant types that will compete with specific weeds of concern. For example, planted grasses will not readily replace shrubs without other tools being used to keep shrubs at bay, but shrubs may replace grasses. Perennial plantings are likely to be more effective than annuals. If the target weed is a shrub, tree or vine that can overtop other planted species and if plantings are not dense enough to inhibit their regrowth, competitive planting will likely fail. Under these conditions, competitive plants can only inhibit regeneration of seedlings and not growth of established plants.

Habitat restoration utilizes the same principles and focuses specifically on restoring ecological functions that have been lost through invasion or disturbance. Native species are planted in target sites or seeds are sown to increase the abundance of native plants and simultaneously to reduce weed populations. Competitive plantings can be most effective when there are at most a few weed species present on the site. It becomes more difficult as the number of weed species and the diversity of traits of those weed species increases. In some cases, non-native species are used in competitive planting projects to initially suppress weed cover while native species are established in a second competitive planting or restoration effort.

Competitive planting is generally more successful when being used to augment an already existing native plant population. In this version of the technique, native plants are added to areas where numerous native plants exist at the site, but native plant cover is below levels found in desirable habitat, possibly due to stressors on the plant population (such as livestock grazing, a fire, long-term drought, etc.).

Competitive plantings are less successful when the weeds being targeted have functional traits that are superior to the native plants they replace, such as greater seed mass, germination rates, plant height, root length, or growth rates. However, some invasive plant species can be reduced with competition from a native plant that has similar competitiveness. Invasive non-native species in California are often better competitors than the natives they replace during at least one portion of their life cycle. In this case, competitive plantings may slow down an invasive plant, but will not provide effective control of the invasive over the long term when used alone.

Competitive planting is most effective when used as one component of an integrated vegetation management program. In many cases, this technique will not work without incorporating pre- and post-planting weed reduction techniques. Regular supplemental weed treatments may be necessary even after the competitive plantings have become mature. Efficacy ratings provided for this technique are based on combining planting with prior weed control treatments to reduce both weed cover and its seed bank. Post-planting weed control will further improve establishment success of competitive plantings. Managers should also prepare to follow up with planting additional competitive plants on a site in subsequent years. This will increase cover to fill in areas where competitive plants may have died or have poor vigor. Although this technique is ineffective at fully eradicating specific weed species, it can substantially increase a site's habitat quality for wildlife and aesthetic and recreational value for people and reduce total cover of weeds.

How to Use

Competitive planting requires a careful understanding of the ecology of the target site. Weed cover should typically be reduced in advance of competive planting. (Methods should be carefully chosen not to impact competitive plantings. For example, pre-treatment disking or prescribed fire at a site may reduce weeds but may also prevent some native plants from establishing because of soil disturbance that favors weeds.) Once weed populations have been reduced below a target abundance or cover level, native plants can be introduced to the site, such that weeds will be impeded by the natives. Use the first year or few years after weed populations have been reduced to promote the establishment of competitive native plants.

There are two general ways of actively establishing native species on a site: seeding or planting (e.g., transplanting seedlings). Seeds of competitive plants can be directly broadcast into a target area. Seeding rates and species palettes will depend on the characteristics of the site, the surrounding habitat, and the weeds present. Assume that some weed species not currently present on a site will appear and that they will also need to be managed. Post-establishment weeding likely will be needed to prevent, or slow, this secondary invasion. Seeds of competitive species typically need to be incorporated into the soil either by hand tools (such as rakes or hoes) or with a seed drill or other mechanical equipment. Seeding into sites with an extensive weed seed bank often leads to failure because weed seeds will germinate and outcompete natives. Therefore, sites without a weed seed bank should be selected or intensive weed control must be conducted (often for multiple years) prior to seeding to reduce the seed bank.

Transplanting seedlings will overcome issues of seedling competition. This can be done by planting potted plants (typically plants ranging from 2 ½-inch starts to 1-gallon pots) into a pre-treated area. (To avoid the spread of soil borne pathogens, including *Phytophthora*, it is essential that potted plants be grown using nursery industry best management practices.) In riparian or marshy areas, plant fragments can be directly transplanted into wet soils from donor sites. Some large shrubs and trees can be 'pole' planted into wet soil (e.g., mulefat or willow) if the species is capable of resprouting. In pole plantings, the bottom of a branch or pole is deeply buried (e.g., 3 feet) where it will root into moist soil and develop into a new shrub or tree with minimal care. When transplanting competitive plants, the same techniques that are used in traditional restoration can be employed. These include irrigating plants,

creating berms and basins, using deeper pots in dry soils, and weeding around transplants. In some cases, shrub or tree shelters will need to be added to reduce browsing by wildlife.

Competitive plants can be transplanted into parts of a site in rows or 'islands,' allowing their seeds to repopulate the remainder of the site in future years. As the first transplants become established, weeds are treated between the rows or around the edge of the islands. Often, after several years, the competitive plants may produce enough seeds and new seedlings will establish adjacent to the areas where the first transplants were planted. Maintenance is also easier because it allows for easy access to control weeds along planting edges. This technique has been used to re-establish shrublands. Colonization of established habitat rows or islands by rodents seems to help with the success of this method, because they forage on weed seeds along planting edges. This method is a modification of the Bradley method of habitat restoration (see Fuller and Barbe 1985). The Bradley method capitalizes on the competitive abilities of resident desirable plants by starting weeding work from the edges of patches of native plant populations and slowly working into more invaded areas over a period of months or years. The Bradley method can be used to break up large projects into small patches of work thereby reducing initial costs, if budgets are constrained.

Over the long term, populations of competitive plantings may decline against weed species encroachment partly due to environmental or small-scale site differences. For example, the cover of competitive plants will likely decline after a multiple-year drought. When average or above average precipitation occurs after a drought, weed species may fill in the gaps between competitive plants. In contrast however, very few native species are lost from an area due solely to invasive plants. There is often a microhabitat where a few natives can thrive while being surrounded by weeds.

Competitive plantings often establish successfully if the planting sites are hand weeded. If plantings are seeded, weeding will need to be around seedlings and span at least the first and possibly the second and even third growing season. After that, as shrubs grow, small mammals can find shelter under the small shrubs to graze on the weeds, which usually happens in intact shrublands. Land managers can often find small mammals grazing on weeds near an existing shrubland edge too, or close to it. Small mammals are less likely to be found far from an existing natural shelter. Competitive plantings near urban and suburban areas may suffer from an overabundance of herbivores. In those situations, herbivore fencing or cages will need to be installed until plants are well established. If small mammal populations plummet, such as during medium- to long-term droughts, then these herbivory patterns can fall apart and weed densities around young shrubs can be unacceptably high.

The species being used as competitive plants matters, as do the species of weeds that are being targeted. Some native perennial grasses and forbs are competitive once established, while many introduced invasives are more competitive in the germination and seedling stages. Other weeds, however, can tolerate high levels of competition. In addition, non-native transformer species (those invasive plants that can transform the structure and function of an ecosystem, such as invasive grasses converting a shrubland, or invasive trees converting a shrubland into forest) are so competitive that their expansion cannot be stopped without intensive long-term management.

The success of competitive plantings is often related to reducing future weed invasions. Other weed control techniques need to be used to get those plantings to the point where they can compete. Focusing only on planting is often not sustainable without combining weed control techniques. Long-term maintenance of desired plant communities may also be key to persistence if there continues to be

import of invasive weeds that may colonize and become abundant on the site. In some habitats, introducing a disturbance regime (such as fire, livestock grazing, flooding, etc.) may help maintain the desired native plant community if natural disturbances are absent or minimal.

Competitive planting projects are often costly unless labor or plant material are subsidized, such as through volunteer labor. In some special situations a land manager may be able to collect local seeds and spread them on a site that has lower than desired plant cover and achieve some success with competitive plants. However, most competitive planting projects require significant investments in pre-planting weed work and propagation of nursery plants. On the highest cost end of the scale, a project can include collecting local seeds, germinating and propagating a suite of locally collected species in a nursery, working with nurseries that have strict pathogen prevention measures, transplanting potted plants in the field where weeds have been reduced prior to planting by other effective weed control methods, placing the potted plants in protective structures, continuing long-term weeding as needed, and irrigating the competitive plants to increase survival rates or mitigate for below-average rainfall. On this end of the scale, costs can easily exceed $5,000 per acre. In some cases, such as when using a modified Bradley method, the major costs for competitive planting sites will be in labor used for weeding which may only equal hundreds to a few thousand dollars an acre, especially if native plants are adjacent to the site. For some, competitive planting projects costs will markedly decline four or more years after the project has started as native competitive plants become established.

If natives are light loving, then planting, especially by seed, several different types of native plants could be competitive. Maintaining gaps between the canopies of native plants is important to help further competitive plants to establish. Conversely, for species that are known to emerge through non-native (e.g., grass) canopies, sowing without weeding might work, though this has not been successful for several pairings, such as coyote brush seeding in non-native annual grasses.

Historic land uses may also play a role in establishing competitive plants on a site. The disjunct between the species assemblages left by indigenous land management and modern approaches may create problems when managing plant assemblages for desirable species. Land management practices have changed drastically over the past few hundred years in California. As land management practices have transitioned from American Indian to Spanish ranchers to today, significant changes in species assemblages and disturbance regimes are present. For example, in some locations fire suppression has created high density, relatively even aged forest stands which then affects other species on the site, including the ability to establish natives. Lack of regular fires in grasslands can alter seedling establishment in grasslands.

Effectiveness of competitive plantings will depend on the ability of competitive plants to suppress target species, by procuring more resources than the target species or by growing taller and shading the target species. If the weeds can tolerate the competitive plants, then the technique will have poor effectiveness. There are a few native species which might prevail in competitive plantings against very difficult weeds, however research on this is limited and some successes might not be replicated elsewhere.

Species that have high rates of spread can disperse to areas where competitive plants are less likely to grow in a dense stand reducing their ability to control those weeds. Considering only a finite area, such as a riparian zone, a high rate of spread would still give the weed some advantage, but in the long run, certain slow perennial competitors, such as valley sedge (*Carex barbarae*), may prevail. In addition,

many invasives are fast-spreading pioneers some of which decline over time against moderate to high competition. Some non-natives initially are abundant after disturbance but can be displaced over time by natives.

In general, if a weed species has a long-lived seed, over the course of several years some of those seeds will disperse to areas where competitive plants are not as dense or tall and those weed seeds may germinate and establish. All other things being equal, short seed life would be easier to control, but such plants often, if not usually, are adapted to spread quickly and widely.

Control of weeds will depend on the ability of the seeded competitive plants to outcompete the weeds. If the competitive plants can germinate before the weeds and access resources first, they will often be able to reduce weed growth. Since most rainfall in California occurs in the winter and spring this technique would be most effective using competitive plants that germinate during those seasons. Native summer annuals (such as tarweeds) may also germinate in the winter and spring, so they may not compete well with non-natives germinating in the same seasons even though they flower at very different times of the year. If the weed species can produce a large number of seeds or propagules, then it becomes more likely that a few plants will establish in a microhabitat that is favorable to the weed and not as favorable to the competitive plants, thus the competitive plants might not be effective at suppressing the weeds.

For upland shrub restoration, when crews work off a calendar and maintain regular visits to work sites (and given adequate rainfall), through a combination of competition and herbivory, weeds can be kept under control. If small mammal populations plummet, as happens after extended drought, the mechanisms break down.

Control of resprouting weed species by competitive plants will be less effective or take longer and risks of the method failing will be higher. If the weed species has the ability to resprout, then the competitive plants must be able to maintain a competitive ability (such as by having a dense canopy) the entire growing season or even the entire year. For species with a limited ability to resprout, it is often easy enough for land managers to treat resprouts during site visits. Other slow resprouters are also easy to treat when they appear repeatedly in buffers between seeded areas.

Control of weeds will depend more on species specific factors and less on flowering season. The control of weed species will more depend on the canopy and growth of the competitive plants and the type of competitive plant. If the weeds and the competitive plants are the same plant type, (i.e., both grasses) then flowering season can influence control effectiveness. If the weeds flower over multiple seasons, then control techniques may take longer. With regular visits, crews can cut back annual species at bud or before flowering and perennials before flowering.

At small scales, competitive planting is a successful technique. As the size of the patch grows, the ability of competitive plants to dominate decreases and the ability of weeds to thrive in specific microhabitats increases. In addition, at small scales workers can easily find new weeds and remove them. There are not many cases where wildlands have been planted with competitive plants at very large scales with long-term successes, notable exceptions include aerial hydroseeding (often after wildfires), and large, flat riparian or mesic areas where agricultural equipment can work the site to reduce weeds during the dry season and seed natives efficiently. Plantings could be effective at reducing weed populations at

these large scales, but challenges with implementation and costs generally prevent projects at large scales, especially on sites with varying terrain.

As slope increases it becomes difficult for workers to manage weed populations or to prepare for planting or seeding competitive plants on steep slopes. Shrublands tend to be found on steep to very steep slopes and so to work with this limitation crews can plant in strips, to reduce erosion and allow seeds to disperse down the slope. Tamping seeds may help prevent seed losses to runoff. However, weeding the first year during establishment can be difficult, especially for workers on the uphill side of strips. Slow spreading perennials or vines might be a good choice for steep slopes as they can spread up or down the slope to reduce weeds.

As access to a site decreases due to the distance from a road, it becomes more difficult to ensure that successful competitive plantings in weed dominated areas receive the amounts of work necessary to reduce the weeds. If weed populations are low, then weeding techniques far from roads are easier to implement. Some techniques can be effectively used far from roads, such as aerial hydroseeding. There may be exceptions to sites far from roads, but since both plants and associate weed cover need to be managed in the growing season, logistics and effectiveness are all that much more challenged. Conversely, working on a site directly adjacent to a road, even a dirt road, may also be difficult as roads can concentrate rainfall and lead to more weed pressure and flash flood environments that would not occur a short distance from a road edge.

Soil texture can be a significant issue when growing competitive plants on a site. Each soil texture (sand, silt, clay, loam, clay loam, etc.) has unique challenges for establishing plants and the weeds that the soils will support. In rocky areas it becomes difficult to establish cover that would outcompete weeds and the cervices can provide places for weeds to get into and establish. Rocky soils can also be problematic as a safety issue for crews on foot. Clay soils can be difficult to work on as crews can transport new weed seeds into the soil on their boots, and the competitive plants that are selected will need to be tolerant of moist soils for potentially months during a wet year.

Grasslands can be a difficult habitat type for competitive planting. Grasslands lack a tall canopy that creates shade and thatch buildup of native grasses can inhibit germination. Native bunch grasses often do not form dense, closed canopy stands, which leaves space for invasive species. Thatch buildup can result in die-off of native grasses; eliminating thatch buildup will assist with establishing other natives between bunchgrasses. In addition, many wildflower species in grasslands can grow between bunchgrasses, including geophytes, and it may prove difficult to reduce weeds and allow for competitive plants to flourish in this habitat type. In some cases, it is difficult to distinguish invasive grass seedlings from native grass seedlings. If workers cannot detect weeds until late in the season, the native seedlings may be reduced or have died due to competition from weeds. The use of native grass plugs can help eliminate some of these difficulties when managing grasslands. The use of biodegradable weed barriers around plugs can help with establishment success by reducing weed pressure.

Rocky or cobbly soils are extremely difficult to work on, especially when trying to dig planting holes for native transplants. It is also difficult for large equipment to drive across rocky soils, and heavy tools may be needed to assist with digging planting tools. There is less available soil surface for plants to establish from seed, as the rocks may take up a portion of the soil surface. It also becomes difficult to remove weeds between rocks.

It becomes increasingly easier to increase competitive plants in areas that are dominated by native plants than in areas dominated by weeds. However, it can be time consuming to plant into a site that has, for example, over 75% native cover, in order to eliminate a species of weed. It can be more efficient to just to do the weed control. At high cover levels, collateral damage can become a problem with weed control work, especially around native annuals or small perennials.

Special Tips

A variety of restoration techniques can be used to establish desirable plant species. Choose a site with existing native vegetation. Focus planting along edges of native habitat to capitalize on adjacent seed rain and herbivory that could keep weeds down (though herbivores may also browse transplants). Tree tubes are highly recommended for oak seedlings, both to improve growth and protect them from deer browsing. When using tree tubes, a porous barrier must be placed over the top to avoid birds getting trapped. Shrub shelters are also helpful for establishing shrubs. Consider temporarily fencing sites that show extensive browsing by wildlife. Consider planting densely to exclude weeds early on and thinning out plantings later as they mature. When transplanting, make sure not to introduce only a single sex of a dioecious species (e.g., willows and mulefat).

Examples of some highly competitive native species are shown below. Verify that a particular species occurs in your region and use local genotypes when available.

Scientific name	**Common name**	**Growth form**	**Notes**
Amsinckia spp.	Fiddleneck	Winter annual	Choose common local species.
Baccharis pilularis	Coyotebush	Shrub	Most upland habitats
Baccharis salicifolia	Mulefat	Shrub	Common in southern and central CA. Riparian habitats.
Croton setiger	Doveweed	Summer annual	Common in southern Ca. Competes with summer weeds
Deinandra fasciculata	Fascicled-leafed tarweed	Summer annual	Common in southern California
Distichlis spicata	Seashore saltgrass	Rhizomatous grass	Saline/alkaline soil
Elymus triticoides	Creeping wild rye	Rhizomatous grass	Oak woodland and grassland
Elymus elymoides	Squirrel tail grass	Perennial bunchgrass	Mountains and Great Basin and Mojave Deserts
Grindelia camporum	Gumweed	Perennial forb	Can persist in degraded grassland
Quercus spp. such as Q. agrifolia, Q. douglasii and Q. lobata	Coast live oak, blue oak, and valley oak	Trees	Creates canopy over time which shades out competition. Grow slowly.

Creeping wild rye (*Elymus triticoides*) may be a good species to highlight for planting in some locations, especially where there is some summer soil moisture. Alkali heath (*Frankenia salina*) may be able to compete against perennial pepperweed (*Lepidium latifolium*) in some wetter areas. Some native annual grasses, such as small fescue (*Festuca microstachys*), and some native bromes (*Bromus* spp.) can be somewhat competitive against invasive annual grasses.

Optimal Conditions for Use

Competitive planting is best done in areas where the habitat of the competitive plants matches the site. Competitive plantings can be effective in mesic (moderate moisture) soils where perennial native rhizomatous or stolon-forming species can suppress weed populations. For sites that are flat and wet most of the spring, wetland perennials would be a good fit (and upland species would be a poor fit).

In many parts of California, the weeds invading a given habitat type are a different growth form than the native plants they threaten, and this affects which areas will be most conducive to effective competive planting. For instance, non-native annual grasses invading areas with native perennial shrubs are most appropriate for areas that are not too dry or too wet, where shrubs are most likely to establish.

In many arid areas of the state, the weed species are annual or occasionally biennials, whereas the natives are annuals and perennials. These weeds tend to have traits that outcompete native annuals and the seedlings of perennial plants, so native seedlings will need assistance (such as irrigation, weeding, or an herbivory shelter) to ensure establishment.

Caveats

The competitiveness of most native plant species relative to invasive plants is either unknown or only known through anecdotal observations. There are few, if any, native species that are known to be highly competitive across their range, in all growth stages, in a variety of plant associations and against a variety of weeds commonly encountered in the environment. Each species will perform differently from site to site.

The principles on which competitive planting as a weed reduction technique is founded are sound, but the technique relies on local environmental factors and specific species interactions that may not have been well studied. Practitioners may have difficulty determining which native plants will provide enough competition to suppress local weed populations.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. Follow general safety precautions for field work.

Cultural resources. Low risk for seeding; moderate risk if significant digging is involved for planting. Surface and subsurface cultural resources should be avoided. Where applicable, obtain pre-disturbance cultural resource surveys and permits.

Habitat. Low-moderate risk. When successful, competitive plantings will build habitat and be a low risk. However, transplanted plants have the risk of carrying *Phytophthora* or other soil or plant-borne pathogens with them, especially if they are transplanted as potted plants into moist environments. Other pests, such as polyphagous shot-hole borer, can inadvertently be introduced with pole plantings of riparian shrubs and trees. Invasive ants, such as the Argentine and red imported fire ant, can be introduced through soil. Ensure that plant material is healthy and free of pests before planting. Use of inappropriate plant material can exacerbate invasive plant issues at a site and impact site resilience and habitat quality. Follow guidelines on seed and plant material transfer zones and use local plant material. Seek expert advice when developing plant palettes. Make sure plant material is weed-free and has been correctly identified.

Sensitive species. Low risk. When done correctly, competitive plantings can build habitat for sensitive species. Take care not to plant species that cannot be utilized for a sensitive species occurring on site. As with other techniques, care needs to be taken that activities associated with planting do not harm sensitive species.

Erosion. Low-moderate risk. Using competitive planting techniques may reduce erosion risk over the long-term when weeds are less able to hold the soil than competitive plants, but erosion may increase erosion risk in the short term by exposing the soil surface. This can be mitigated with mulch or other temporary soil cover.

Other Non-Chemical Methods to Combine With

Competitive planting techniques often must be combined with weed reduction methods before and after competitive plants have been introduced to the site. Examples of non-chemical weed reduction techniques that complement planting include hand pulling, hoeing, grazing, prescribed burning, solarization, and mulching.

When Not to Use

Perennials with a strong ability to resprout will be difficult to control with this technique. Weedy vines (such as morning glories, *Convolvulus* spp.) that can overtop natives will be difficult to control.

There are several species against which few, if any, competitive natives might prevail, these species will spread underground and eventually occupy the soil (*Lepidium latifolium*, *Calystegia sepium*, *Pennisetum clandestinum*). Oats (*Avena* spp.) are also a highly successful invader in more mesic to somewhat xeric habitats. Other invasive annual grasses (some *Bromus* spp.) produce an abundance of seed, are early sprouting and maturing, and thus capture resources more effectively than native annuals.

Photographs

Left: Site preparation with Mcleod rake before planting to remove weeds. Photo credit: Cal-IPC. Right: Planting gumweed in a degraded grassland using a dibble as a planting tool. Photo credit: Tanya Meyer.

After prepping site through grow-and-kill with herbicide and mowing, this site in Irvine was replanted. Left: Seed imprinter to improve seed-soil contact. Photo credit: Megan Lulow. Right: Seeding needlegrass with a wildland seeder. Photo credit: Lars Higdon.

Sequence of planting shrubs into thatch of dead ice plant. Left: Volunteers plant shrubs. Center: One year after planting, with ice plant mulch suppressing weeds. Right: Three years after planting with no supplemental water after first year. Photo credit: Riley Pratt.

Competitive doveweed (*Croton setiger*) and tarweed (*Deinandra fasciculata*) are increasing in abundance after grass removal treatments in this highly invaded grassland. Note lack of natives on right side of fence. Photo credit: Christopher McDonald.

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Supplementary Information

None.

5.2 Burning

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Overview

Fire has been used by many cultures over millennia to clear land of woody vegetation or to stimulate growth of preferred plant species. Today, prescribed fire is one tool used to treat invasive plants, reduce fuel loads, and maintain habitats in fire adapted landscapes. In California, it has been used by land managers mainly as a tool to suppress non-native annual grasses in grassland habitats. Eradication of weed populations is unlikely using fire alone, but it can be a valuable part of an integrated weed management approach when used properly.

Fire removes thatch and aboveground vegetation. Depending on timing and intensity, it can also kill seeds and expose bare soil. Its effect on habitat is dependent on pre-fire plant community, timing, intensity, and burn frequency. As a tool to manage invasive plants, prescribed fire works best on annual grass species with fire-sensitive seeds that are short-lived and retained in seed heads until at least late spring. In lower elevation grasslands in California, prescribed fire has been used most effectively on barbed goatgrass (*Aegilops triuncialis*). Under optimal conditions, it has also proven to be moderately effective on medusahead (*Elymus caput-medusae*), ripgut brome (*Bromus diandrus*) and yellow starthistle (*Centaurea solstitialis*). Invasive plant seed banks must be managed with consecutive seasonal burning; however, successive burns in years 2 and 3 are often difficult due to reduced fuel load.

Fire does not always favor desirable species. Along with reducing target plants, using fire in grasslands can also lead to an increase in non-native broadleaf forbs. When used in shrublands, perennial grasslands, or riparian habitat, fire can negatively impact beneficial perennials and increase non-desirable species. Fire-tolerant weeds, especially where they are already established at low densities, are most likely to increase.

Though fire is not very selective, land managers can often avoid damage to desirable trees, shrubs, and other perennials with a well-managed, lower intensity burn. Fire should not be used in habitats that are not adapted to fire, such as desert scrub or most riparian systems.

The success of a prescribed fire at controlling a target weed will depend on timing, fuel load and fire intensity. Whereas high fire intensity may be most effective at killing seeds, it also increases the potential to kill desirable perennial plants. High intensity fires are more difficult to control.

Fire is less common as a management tool than it once was in California, due to air quality concerns around population centers and the recent increase in large, destructive wildfires throughout the state. Public safety is the most important factor in determining if a prescribed fire can be conducted. Impacts to native ecosystems, sensitive species, and cultural resources must also be evaluated.

How to Use

Burning requires substantial planning and coordination. Burn plans, permits and protocols specific to the local area, local fire agency approval and air quality permissions are all required. A plan typically takes from one to four years to complete. The plan outlines implementation protocols, assesses risks, and is typically valid for three to ten years. The proposed date of each burn is then selected several months ahead of time. As the burn date approaches, the lead implementing agency will track weather and air quality forecasts and modify the date as needed to meet safety and air quality standards. Local fire agencies can provide information about local ordinances and regulations that may affect timing and feasibility.

The California Department of Forestry and Fire Protection (CalFire) is a key partner in most burns. Through their Vegetation Management Program, or VMP (https://www.fire.ca.gov/programs/resource-management/resource-protection-improvement/vegetation-management-program/) they generally take on a significant portion of the costs associated with implementing a burn and assume the liability if a fire escapes containment. Associated costs to the landowner and land manager generally include staff time for preparing a VMP plan, coordination with CalFire and other partners, and the per-acre fee in the Smoke Management Plan (i.e. smoke fees). Local and state firefighting authorities may use a prescribed burn as a training opportunity, in which case the lead fire agency will usually take care of all necessary permitting. This can reduce the costs and time commitment required by the land manager.

Burns on public lands can only be conducted by trained and certified individuals. The Red Card (also known as an Incident Qualification Card) is an interagency certification held by a person qualified to work on an active burn. Significant site preparation is required to limit the fire to the target area. (If sites are remote, off-road vehicle access needs to be permitted.) Burn perimeters get marked and assessed, minimum width of perimeter lines is determined based on the height of adjacent vegetation, and final line locations are decided. Then lines are cut, typically by crews using hand tools to obtain the minimum widths of mineral soil and adjacent fuel reduction zones where vegetation is typically mowed to a few inches in height. On the day of the prescribed burn, hose lays (hose placed on the ground within the perimeter line) can act to enhance secure perimeters.

The success of an invasive plant management burn is dictated by timing and burn intensity. To be most effective, burns should be conducted before seed set or seed release and after fuels have dried sufficiently to carry a fire hot enough to kill seeds. Successive burns that occur 2 to 3 years in a row at the optimal time to kill seeds are the most effective but are difficult to achieve due to reduced fuel loads in years two and three. In dry environments, burns are most effective and least harmful when conducted in a wet year because desirable perennials plants and trees can more easily recover from fire damage, and because the fire will have sufficient fuels to travel across the burn or management unit. Assuming burns occur in optimal conditions and are repeated, fire can successfully suppress barbed goatgrass, medushead and ripgut brome because their seeds remain on the plant later than most species and because their seeds may be more susceptible to heat than other grass species. By remaining in the grass canopy, their seeds are exposed to higher heat from fire than the seeds of species that have dropped to the ground, such as wild oats (*Avena* spp.) and soft-chess brome (*Bromus hordeaceus*). Plant phenology must be monitored to ensure burns are conducted no earlier than the “boot” stage for target grasses (when flower heads have formed and are just about to emerge) but prior to seed drop. In most

years, there will be a relatively short window when fuels have dried sufficiently to carry fire and when seeds of target species have not yet dropped.

Yellow starthistle can also be controlled by burning in early summer before viable seeds are produced but after fuels have cured. In the field, this translates to the early flowering stage (2 to 5% inflorescences flowering per plant). As with the grasses, burns must be under optimal conditions for at least two consecutive years and effective second year control is often difficult because of lack of fuels.

Without additional follow-up, non-native annual grasses and yellow starthistle will recover once treatments are stopped, generally returning to pre-treatment levels in 2 to 4 years. Complete burns are more effective than burns where there are unburned or lightly burned patches. Achieving complete burns (nearly 100% fuel consumption) multiple years in a row can be difficult because new fuels may not accumulate quickly enough. Treatment effects may last for up to three years and longer for barbed goatgrass.

Special Tips

Temperature, fuel load and intensity of a burn can be modified by the following techniques:

- Burn when vegetation moisture content is higher to reduce risk of fire escape and damage to desirable perennial vegetation. The timing and amount of precipitation will determine this window of opportunity in any given year. Higher fuel moisture content in late spring will generally prevent fire from burning into chaparral and minimize damage to oak trees in open woodlands and savannas.
- In native perennial grasslands in years with normal precipitation, there is a short window of opportunity to maximize the efficacy of fire in treating invasive species. The window is usually a 4-week period before target non-native annual species drop their seeds and when perennial grasses will readily carry fire.
- Head fires, the leading fronts of fires, are hotter and burn more material because they move in the direction of the wind or up slope.
- Use back burns that are ignited along a fire break ahead of a head fire to reduce fuel available for a head fire. By burning smaller areas, usually into the wind, back burns generally burn cooler, more slowly and will leave more standing biomass than head fires.
- Mowing and back burning can be used to protect sensitive resources, including riparian areas, oaks, occupied nests, or cultural sites. Mowing is completed to allow safe ignition close to the sensitive resource under conditions that result in the fire burning slowly away from the resource. The result is a black area around the sensitive resource that prevents the head fire from burning into it.
- Cut non-native grasses, forbs or woody species and allow them to cure or dry on site before burning to increase fire intensity.
- Seed non-invasive annual grasses prior to second- and third-year burns to increase fuel loads for successive burns.

Optimal Conditions for Use

This technique works best when implemented just before flowering stage or at early seed set of the target plant and when a site has sufficient dry fuel to carry a burn. Burning under these conditions will generally not be possible if the targets are annual grasses as they need to cure before carrying fire and they do not cure until after seeds are produced. For annual grasses, this technique works best when used as soon as grasses have cured enough to carry fire. This will maximize the amount of seed held on the plants and thus seed mortality.

Caveats

Burning may facilitate the spread of other weeds that were not specifically targeted. These include many species of broadleaf forbs and perennial invasive grasses such as Harding grass (*Phalaris aquaticus*), fountain grass (*Pennisetum setaceum*), and velvet grass (*Holcus lanatus*). Burning also has the potential to negatively affect the seed production and vegetative growth of desirable plant species. It is important to have good information on your pre-burn plant community to anticipate how desirable species may be impacted and how disturbance following weeds may benefit.

Several conditions may prohibit the use of burning as a management tool:

- Air quality conditions and regulations.
- Regional fire danger (influenced by wind conditions, humidity, temperature, and vegetation moisture content).
- Presence of surrounding development or sensitive infrastructure.
- Presence of sensitive biological or cultural resources.
- Lack of skilled/trained personnel.
- Logistical or other constraints on optimal timing.

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low-moderate risk. Fires can kill, and smoke impacts air quality which can cause respiratory issues for people and animals. Planning requirements and permits are designed to minimize these hazards. Prescribed fires should only be conducted by qualified and trained professionals. Depending on land ownership and local jurisdictions, federal fire agencies, CalFire, and local fire agencies must be consulted and under most situations will take the lead in conducting the burns for the land management organization.

Cultural resources. Low-moderate risk. Known cultural resources should be protected during prescribed burns. Discuss protection measures with fire crew leads. Unit boundaries can be modified to avoid sites or protected as “stay-out zones” within larger units.

Sensitive species. Moderate risk. Risks to sensitive species (e.g., birds, rodents, reptiles, arthropods, and desirable plants) should be considered prior to burning. The ideal timing for a burn, based on the effectiveness in controlling the target weed species, may overlap with timing that results in negative impacts to sensitive species, for instance nesting birds. Ground nesting bird surveys must be conducted prior to prescribed burns being conducted during the nesting season. A qualified biologist should

delineate an area around each nest to be protected from fire. In grasslands, mortality of snakes and lizards is common in a burn. Most grassland small mammals are protected from the heat of fire in their underground burrows, but in the short-term their food resources will be reduced. Small mammals that build aboveground nests (e.g., woodrats) will likely be killed. If there are goals to minimize negative impacts to rare plants and other organisms (e.g., listed butterflies) when they are at a stage that makes them vulnerable to fire, surveys should be conducted. If detected, the perimeter of the burn can be modified to avoid impacts or firing techniques can be used to leave unburned islands within the footprint of the burn to minimize impacts. If it is necessary to leave unburned areas within the prescribed fire footprint, it will decrease the treatment effectiveness. These areas should be treated once it is appropriate, or they will act as sources of recolonization by undesirable species.

Habitat. Moderate risk. Fire can negatively impact many native habitats in California without proper planning and implementation. Most riparian habitats and desert habitats will be negatively impacted by even a single fire, leading to loss of native perennial species, rapid invasion by a suite of non-native species and often type-conversion to non-native dominated plant communities. Too frequent fire will lead to type conversion of native-dominated shrublands, such as chaparral and coastal sage scrub, to non-native annual grasslands. Thoughtful consideration should be given to using fire for targeted weed control in these communities as removal of the shrub canopy will lead to an increase of non-native herbaceous species present in the understory and adjacent areas before the burn. If undesirable and highly invasive species are present, they will proliferate and may greatly decrease the diversity and cover of native species.

Erosion. Moderate risk. Fire has the potential to remove all aboveground biomass protecting the soil from erosion. Significant soil movement, sediment deposition, and mudslides can occur following fires on steep slopes. Therefore, it is recommended that prescribed burns should not be conducted on steep slopes as there could be loss of beneficial topsoil, impacts to human infrastructure, and loss of sensitive aquatic habitat.

Other Non-Chemical Methods to Combine With

Fire is best used in combination with other techniques to improve its effectiveness and reduce the risk of unintended impacts. Fire will remove standing biomass to allow more effective detection and follow-up treatment of target species. Fire can also flush the seedbank of target species to accelerate target species suppression. Care must be taken to ensure resources are available to treat seedlings for multiple years if fire is used to flush the seedbank. Mowing non-target species and allowing cut material to cure prior to a burn will result in hotter fires that may kill more seeds or perennial species. Mowing can be effective as a follow-up after target species have re-sprouted or germinated the following year. Solarization and manual removal can be used to improve target species control following a prescribed fire.

When Not to Use

Do not use fire as a management tool to treat weeds in native shrublands. Repeated burning will kill shrubs and lead to type conversion to non-native annual grassland. Burning is not an effective control method for rattail fescue (*Festuca myuros*), many annual non-native forbs, and most biennial and perennial weeds with underground storage structures.

Photographs


Left: Mowing and back-fire lighting technique to "ring an oak," protecting Engelmann oaks (*Quercus engelmannii*). Right: Lighting a head fire to maximize fuel consumption and mortality of non-native annual grass seed. Photo credit: Carole Bell.


Left: Hand crew maintaining a mowed fire line at the Santa Rosa Plateau Ecological Reserve in preparation for a prescribed burn. Right: Putting out a controlled burn. Photo credit: Carole Bell.

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Supplementary Information

In California, only six species were reported to be targeted for control using fire by more than one source (contributor and/or literature). The six are barbed goatgrass, ripgut brome, medusahead, yellow starthistle, French broom and Scotch broom. Goatgrass seems to be the species that is most effectively controlled by burning. Reports of unsuccessful control efforts using fire for each species were more common than successes. Successful control of a target species often resulted in a shift to communities

dominated by non-native annual forbs. Despite the lack of success of fire to control or eradicate individual species, there was some consensus that fire is a valuable grassland management tool in California. Removal of non-native annual grass thatch, returning a natural process to the land, short-term suppression of non-native annual grasses, and maximizing native species diversity with an intermediate disturbance regime were the primary reasons stated for justifying the use of fire in grasslands.

Barbed goatgrass, medusahead, and yellow starthistle were the three species most frequently reported to be targeted for control or suppression using fire. Ripgut brome was the only other species regularly targeted for control (DiTomaso et al. 2006, Moyes et al 2005, Principe personal experience). There is, however, extensive use of fire reported to manage grasslands dominated by non-native annual grasses. Non-native annual grasses species respond differently to fire. Amatangelo et al. (2008) found that large-seeded species and small-seeded species responded differently to various levels of shade and litter. Both shade and litter are altered by fire. DiTomaso et al. (2006) and unpublished data from Santa Rosa Plateau Ecological Reserve (SRPER) indicate fire effects on annual grasses are more strongly tied to how long seeds are retained on the plant and the susceptibility of seeds to heat than to seed size. In general, at SRPER, effectiveness one year following a single fire was Fair to Excellent for brome grasses (*Bromus diandrus*, *B. madritensis* and *B. hordeaceus*), Fair for wild oats (*Avena* sp.), and Ineffective for rattail fescue (*Festuca myuros*), which was found to increase following some burns (Principe unpublished data). DiTomaso et al. (2006) report the seeds of *B. diandrus* and *B. madritensis*, along with medusahead and barbed goatgrass, remain in the inflorescence longer than most grasses, where they are susceptible to being killed heat. Marty (2015) found non-native annual grasses as a functional group were reduced by 35% for one year following a single burn. Marty (2015) and data from SRPER (Principe unpublished data) indicate non-native annual grass cover quickly returned to pretreatment levels without treatment, often within only one year, but almost always within four years.

Many non-native annual forbs respond positively to fire. Marty (2015) found results similar to those at SRPER, where non-native annual forb cover increased after burning. Marty (2015) also found non-native annual forb cover was nearly 100% greater in burned plots than unburned plots, but only for a single year. Following fires at SRPER, *Erodium* increase by two to ten times in the first year after fire. Moyas et al. (2005) found black mustard (*Brassica nigra*) more or less replaced ripgut brome in the first year after a fire as the dominant species. Interestingly, if non-native annual grasses are replaced by late-season non-native annual forbs like yellow starthistle or summer mustard (*Hirschfeldia incana*), early season annual native forbs can reach extremely high cover and set seed before non-native forbs increase in size. Owl's clover (*Castilleja* sp.) has been observed to do this in both northern California at grasslands sites with yellow starthistle and southern California at sites with summer mustard. However, non-native forbs still tend to dominate end-of-season cover estimates in areas where grasses have been replaced by forbs, which may result in underestimating the positive influences on grassland community composition despite the lack of successful target species control. Yellow starthistle was the only non-native annual forb reported to be targeted using fire in California by experts and the literature indicating the widespread recognition that fire is generally not effective against this functional group.

DiTomaso et al. (1999) report it took three consecutive years of burning to reduce the yellow starthistle seedbank by 99%. DiTomaso et al. (2006) and experts interviewed for preparation of this document reported using fire combined with herbicide greatly increases effectiveness of control. Plant phenology must be monitored to ensure burns are conducted when the first flowers are being produced.

D'Antonio et al.'s 2006 meta-analysis of 28 studies assessing fire effects in California grasslands did not find a consistent effect of fire on native or exotic species, because non-native species or functional groups are generally replaced by other non-native species after fire without additional treatment.

It is difficult to control biennial and perennial herbaceous species with fire. DiTomaso and Johnson (2006) report examples from eastern states of fire successfully controlling perennial grasses but report no successes in California. DiTomaso and Johnson (2006) report most of the problematic invasive woody species resprout from the base and are thus difficult to control with fire. Fire effectively kills mature broom (e.g., French [*Genista monspessulana*] and Scotch [*Cytisus scoparius*]), but fire flushes the broom seedbank. Multiple fires reduce cover, but broom recovery is relatively fast once treatment is stopped due to the long-lived seed bank. Broom control requires a long-term commitment using multiple strategies including cutting, herbicide and/or seeding with grasses (non-native annual) to increase fuel loads after the first burn treatment (DiTomaso and Johnson 2006, NPS staff personal communication).

Working with partners can make optimal burn timing difficult to achieve. As a result of non-optimal timing of burns, a long-term prescribed fire program in southern California grasslands found widely variable responses of a suite of annual grasses to burning (Principe unpublished data). Here, even the primary target species, ripgut brome, which is frequently reduced by over 90%, occasionally is not effectively controlled due to fires being conducted too late.

Non-native annual forbs generally increase after fire, especially *Erodium* species. Marty (2015) and data from SRPER found significant short-term increases in non-native annual forbs, primarily because of increases in *Erodium* cover. Fire and other disturbances are often used to stimulate germination of the non-native forb seed bank to improve follow-up treatment efficacy. As a result, a single fire with no follow-up treatment may result in greater non-native forb cover (see discussion above). The only forb reported in the literature or by experts to be targeted solely with fire was yellow star thistle. Multiple well-timed complete burns can significantly reduce the cover and seed bank of yellow starthistle under optimal conditions (DiTomaso et al 1999; Kyser and DiTomaso 2002). Despite this one example of yellow starthistle being controlled with fire, all experts reported using other techniques combined with fire to try to control this species as fire alone was not effective.

DiTomaso and Johnson (2006) report most highly invasive woody species are difficult to control with fire, in part because many problematic species tend to increase following fire. There are many examples of "undesirable" native trees and shrubs that are more susceptible to fire than invasive woody species.

Rate of plant spread and seed production of target weeds does not seem to affect efficacy of burning for their control, as three species with high rates of spread (barbed goatgrass, yellow starthistle, and meadusahead) can be controlled with burning. Seed life appears to have more of an impact. Species with longer-lived seeds are more difficult to control in successive years with fire. Winter annuals are controlled more easily than plants that germinate opportunistically or in other seasons.

In southern California oak woodland understory, fire does not appear to be an effective tool to suppress non-native annual grasses, including ripgut brome. Higher fuel moisture in the understory result in poor fuel consumption which leads to minimal impacts to seeds of target weeds and the thatch/litter layer is largely left intact (Principe unpublished data).

If fire is the only tool employed, there are a suite of highly invasive non-native species from all functional groups that can proliferate with its use. Common California invasive perennial grasses such as Harding grass, velvet grass, and fountain grass (*Pennisetum setaceum*) can benefit. DiTomaso and Johnson (2006) state, "Typically, controlled fires or wildfires promote invasive perennial forbs." This includes onionweed, knapweeds, fennel, artichoke thistle and poison hemlock (biennial). Many highly invasive annual forbs, such as thistles, tocalote, yellow starthistle, mustards, and *Erodium* increase after fire. Moyes et al. (2005) reported black mustard (*Brassica nigra*) became a near monoculture after a single burn used to reduce the cover of ripgut brome. *Arundo* (*Arundo donax*), brooms, and tree tobacco (*Nicotiana glauca*) respond vigorously after fire. Other invasive woody species that increase following fire include Japanese honeysuckle (*Lonicera japonica*), tree-of-heaven (*Ailanthus altissima*), Russian-olive (*Elaeagnus angustifolia*), saltcedar (*Tamarix ramosissima*), sweetbriar rose (*Rosa eglanteria*), Himalaya blackberry (*Rubus armeniacus* [=*R. discolor*]), cutleaf blackberry (*Rubus laciniata*), English hawthorn (*Crataegus monogyna*), and common pear (*Pyrus communis*) (DiTomaso and Johnson 2006 citing Pendergrass et al. 1988).

5.3 Grazing

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Overview

Grazing by cattle, sheep, and goats can be used as a technique for controlling weeds. There are differences in effectiveness among grazers depending on weed species and environments being targeted, but in general grazing (herbivory) for weed control varies more by the plants being grazed than the animals grazing them.

In recent years, land managers have begun to consider grazing and browsing not just in terms of livestock production for food and fiber, but as a means of managing for the sustainability and healthy function of California's ecosystems. Livestock can control the mass, height, and cover of herbaceous vegetation and reduce the encroachment of shrubs into grassland. In addition to covering the use of grazers for targeted weed control, we discuss their use as ecosystem engineers, altering and improving habitat by herbivory, trampling weeds, reducing fuel load, altering soil compaction, or providing other byproducts of animal behavior. Grazing and browsing (collectively called grazing here) are not effective as a single-event solution to a weed problem and only work to remove target vegetation when managers can attract and constrain animals to the target area. Grazing can successfully slow the spread or suppress populations of weeds but is very unlikely to eradicate large populations without potentially damaging desired vegetation. It should be viewed as a supporting practice for long-term management or slowing spread while other control methods are being brought to bear.

Livestock are effective at reducing biomass, height and cover of non-native annuals and preventing shrub encroachment on California's annual grasslands and woodlands. They can be used to target specific weeds by managing the time, frequency and intensity of grazing or browsing. This is best accomplished with fencing, attractants and selecting the appropriate species based on class (sex and age) and experience.

In general, cattle prefer to graze on palatable plants that provide the most bulk (biomass) - usually, grasses. Sheep and goats are less able to process lots of cellulose, so they typically pick plants and plant parts that have higher amounts of easily digested sugars and are lower in complex fibers – this means leaves, seeds, and cambium (inner bark). Sheep often prefer broadleaved herbaceous plants (forbs), but will use grasses, especially leaf material and fine stems. Goats prefer leaves and immature leader twigs of shrubs and trees, and the cambium layer of trees that have soft outer bark. Cattle and sheep are commonly described as "grazers" and goats (like deer) as "browsers." Cattle have wide mouths and will use their tongue to rake in mouthfuls of vegetation (low selectivity). Sheep and goats have narrower mouths, which allows them to selectively nibble off parts of plants. There is a fair amount of "plasticity" in these animals, however. Individual animals, and even whole herds, can develop skills for utilizing plants in ways that do not entirely follow these generalizations.

Each situation and opportunity for weed control is unique to the area and the species being targeted. Cost can range from providing an income, if you are using livestock that are already on-site and you are being paid to graze, to being more costly than other management methods if you have complex grazing needs, no infrastructure, and no animals on-site. On an area basis, it is more expensive to graze small acreages than large acreages because of the economy of scale. It is easier for an animal owner to move livestock to a larger area where they will be longer than moving them between smaller sites frequently.

How to use

Grazing and browsing can alter the structure and vigor of plants. Experienced and observant managers can selectively use animal species, densities, and previous foraging experiences together with specific timing and frequency of grazing events to control particular plants. Different scales of weed invasion and different species require different approaches to grazing. Small weed patches are challenging because it is hard to focus animals on them. Large target areas, in contrast, typically will require more animals than feasible. Techniques to concentrate animals such as temporary electric fencing, supplementation (feed hay on top of target plants, place supplement tub in area, or the application of molasses) may work to target areas in large pastures.

Livestock can be "trained" to eat some weed species they do not initially show an interest in. This does not mean that animals will ever exclusively eat these weeds; however, they are more likely to eat them along with the forage they encounter. Several training methods have been developed, including placing hay or molasses on top of the target plant. Kathy Voth's method (https://extension.sdstate.edu/cows-eat-weeds) is the most common training practice currently used by targeted browsing experts.

Plant secondary chemicals (for example, tannins) can affect livestock digestion and health. Protein supplementation may reduce the effects of secondary chemicals somewhat. Animals fed low-nutrient dead or dormant vegetation, like late season annual grasses, will likely need energy and protein supplements to meet nutritional requirements. Land managers should expect this and plan for suitable locations to place the supplemental feed sites. Areas might include dense weedy sites or other areas away from sites that need more protection.

High intensity grazing of grasses and forbs must occur as the target plants are leaving the vegetative growth stage and beginning to flower, but prior to seed set in order to prevent regrowth. Woody species can be controlled at a wider range of phenological stages but are generally most palatable to browsers when producing new growth. Seeds are not always damaged by passing through the digestive tract of animals. This is especially true of grass seeds. Grazing and browsing timing will vary from year to year with temperature and soil moisture, requiring frequent site visits. The longer the target plant can propagate, the more challenging the control.

Timing and frequency. Livestock grazing is most effective at suppressing invasive weeds when it prevents seed production of annual plants, or others that similarly rely mainly on seeds for reproduction. Generally, a plant has the most difficulty recovering if it is grazed between the time when the flower head is ready to emerge (boot or bud stage) and full bloom. For grasses, this means the boot stage. This is a short period of time just before flowering. Timing will vary year to year with precipitation and temperature, but usually, there will be roughly a two-week window for grass species. To control forbs, the best time to graze is during the bud stage, when plants are "bolting" (sending up a flowering stalk). In Central California, the bud stage of many forbs occurs as annual rangelands are entering the

dry season. Timed properly, grazed grasses and forbs will not have enough water and nutrients for regrowth and seed production.

Any grazing done prior to this window may not reduce targeted plants since there may be enough water and nutrients for plants to regrow. In some cases, using repeated grazing may be necessary, but care should be taken if there are susceptible desired plants. In some instances, the period when weeds are most susceptible also coincides with desired plants. Monitoring desired and targeted species is necessary, and grazing should stop if desired plants receive too much pressure. On California's annual rangelands, the dominant species are typically introduced annual grasses such as soft chess (*Bromus hordeaceus*), wild oats (*Avena fatua*), foxtails (*Hordeum sp*.) and/or Italian rye grass (*Festuca perennis*) which may still provide the desired ecosystem services. In comparison, Medusahead (*Elymus caput-medusae*) and barbed goatgrass (*Aegilops triuncialis)* are invading annual rangelands and reducing ecosystem services. These invasive annual grasses mature later than other annual grasses except for annual rye grass, typically maturing in late May to early June. This difference in maturity can be used as an advantage to control these species when grazing is delayed until after seed set of desirable species. Native perennial grasses are most susceptible to grazing when flowering (spring and summer depending on species). If there are native perennial grasses in the area, care should be taken to ensure natives are not overgrazed. This may mean moving animals out of the area before goals are met for targeted species.

All livestock species will browse on shrubs and trees. Cattle and sheep will preferentially select seedlings and resprouts, whereas goats will reach up to browse growing ends of mature shrubs. Livestock can be introduced into areas recently cleared of shrubs (e.g., following shrub removal or after a wildfire) to browse on the palatable young shrubs and trees. Browsing after shrub control treatments can extend the results of the original shrub removal. In the case of a wildfire, livestock can help suppress shrubs, increasing grasses. Livestock may preferentially browse some shrub species, but usually target new growth regardless of species. Browsing 50-60% of axillary and apical buds of shrubs in the dormant season (winter) can hinder spring regrowth. Defoliation is generally more detrimental to shrubs than it is to grasses. Successful shrub management may periodically require higher stock densities and ongoing grazing to prevent shrub encroachment and establishment. Note that although livestock can browse and impact shrub species, they may eat grasses and forbs first, particularly in the green season. It is important to keep monitoring the situation. Practitioners should be aware that removing the native shrub canopy will increase non-native plant cover in virtually every plant community in California.

Grazing Intensity or Stocking Rate. Stocking rates (animal units per unit of grazable forage) must be adjusted to maintain effective grazing intensity as site productivity varies. Well-defined goals for the condition of the site must be established. For example, targets for residual dry matter (RDM – the amount of dry forage measured in September that will be present to protect soils from winter erosion and create a microclimate to germinate new seedlings), habitat structure and/or composition, and sensitive species impacts should guide management decisions and adjustment of stocking rates, as well as duration of grazing in any given year. This is the art of grazing: monitoring the land and watching for signs to increase or decrease livestock for the desired effect. It will take time to develop a relationship with an operator to meet target plant control goals. During this time, the grazing project will require frequent monitoring and communication with the operator. It may be necessary to feed supplements or use temporary fencing to achieve the stocking rate for a specific area. When determining the stocking rate, the size of the area, percent of target species in the area, amount of palatable vegetation, and slope should all be considered. The local manager's experience with their livestock, and supplemental

tools to encourage targeted grazing should also inform stocking rate and appropriate stock density. A higher number of animals for a short period of time will reduce selectivity by increasing grazing competition, resulting in more uniform grazing. If the target species is very palatable, lower numbers for longer periods of time are possible, though control of the target species may be patchy as a result. Constantly monitoring the progress of the livestock in relation to goals is key. See Supplemental Information for more on stocking rates and developing grazing prescriptions.

Target weed species should be monitored for the correct stage of growth to be susceptible to grazing impacts. Early season drought will cause all species to mature earlier than usual. While grazing during the dry season may help reduce biomass, it will not typically stop the return of invasive weeds that have already set seed. Additionally, sources of dry-season water and protein supplementation may be required to allow livestock to graze dry plants without losing too much weight. During wet periods, managers should consider the risk of increasing soil compaction if high animal densities or prolonged periods of grazing are used.

Cattle. Classes of cattle include cow-calf pairs, dry cows, stockers, and bulls. See Supplemental Information for a definition of each class. Each class will exhibit different grazing behaviors. Stockers and dry cows will travel farther from water than cow-calf pairs. Experience can play a big part on how willing an animal will be to graze a weed species. If the animal has grazed the plant in the past, they are more likely to do so again. If dry cows or cow-calf pairs are brought to a novel area, they will be less likely to try new species of plants they encounter, and typically will not travel as much of the new pasture compared to stockers.

Sheep. Sheep will often have a guardian animal with them to protect from predators, typically a guardian dog, but potentially a llama or a donkey. Some flocks will also be overseen by a fulltime herder. If sheep are used to control weeds, there is a greater chance that the project will have adult ewes (equivalent to dry cows). If ewes with lambs are being used to graze, there may be more concern for predators and weather conditions that may affect young lambs. Solar powered woven wire electric fence is often used with sheep to keep them in a small, defined area for grazing. See Supplemental Information for definitions of sheep classes and reproduction.

Goats. Goats tend to be more willing to explore and test fencing and equipment, may be more curious, and sometimes more aggressive than sheep. This means they can require more experience and better equipment to maintain and manage successfully. Fencing is like sheep fencing, with solar powered woven wire electric fence commonly used. If goats are being used to control more herbaceous and less woody plants, a secure fence is needed so they do not escape the grazing area to search for “greener pastures.” Properly selected, experienced, and conditioned goat herds are likely to make better use of difficult terrain and vegetation (especially brush) than other domestic livestock species. However, those environments are also among the most difficult to construct and maintain effective temporary fences in. Goats can also climb on woody plants to some extent, so fencing should be carefully placed so that shrubs and trees do not provide goats with a ladder out of the intended grazing or browsing area. See Supplemental Information for descriptions of goat classes, reproductive cycle, and common breeds.

Special Tips

While the information presented here is provided to help aid you in selecting grazing and/or browsing, there are many more variables in designing a successful grazing management plan than we can address here. For the best end product, please consult with a professional range manager – a Certified Rangeland Manager, local UCCE Livestock Advisor or local Natural Resource Conservation Service Range Conservationist. A site visit will also be necessary to ensure a well thought out plan is created for your situation.

An inventory of plant species should be done prior to beginning weed control. The inventory should include location and density of weeds as well as locations of sensitive plants that should be protected from animals and toxic plants that could harm livestock. Knowing your starting point will help aid you in determining the success or failure of any control measure as well as help aid you in selecting the appropriate tool(s) and method(s) for control.

Use photo monitoring to establish a visual record of control efforts. Permanent markers (fence posts) can be installed or used, and direction described to repeat the photo in subsequent year using either a digital camera, smart phone, or tablet. In addition, apps are available to help manage photos over time.

Some treated sites may appear “overgrazed” for weeks to months following initial treatments. Done properly, however, the site will recover in the next growing season, and dramatic changes in appearance will not be common in the future. If the property is public, or easily seen by the public, some educational outreach will be important to explain the restoration process. Signage with before and after pictures may suffice to communicate the undesirable “before” state, the intermediate state after grazing, and the desired “after” state with reduced undesirable species allowing for more ecosystem services such as habitats for native wildlife and plants, water quality, reduced wildfire risk, and viewshed quality, to name a few.

To prevent accidental introduction of weeds to new locations, animals should be fed weed-free forage for 24 to 48 hours after grazing an infestation and kept in a holding area where weeds germinating from seeds that have passed through animals can easily be detected and controlled.

Optimal Conditions for Use

Graze a target weed just before flowering to maximize effectiveness. Its stage of growth (phenology) should be regularly monitored leading up to grazing. An early dry season will result in plant species maturing earlier. Additional water sources and supplementation may be necessary to encourage or sustain grazing in an area long enough to meet control goals. While this will take extra monitoring, it can be an optimal time to control species since drought conditions may not allow for regrowth, and therefore reduce seed production. Optimal site conditions include low cover of sensitive or other desirable species that are vulnerable to grazing.

Caveats

Some native grasses are most susceptible to damage from grazing during flowering (late spring and summer, depending on species). This often coincides with the flowering periods of some invasive species. If there are native perennial plants in the area, care should be taken to ensure they are not

being grazed very heavily in that critical window or if necessary, the treatment is not repeated in the same location season after season.

Grazing and browsing, even at high intensity, are seldom effective at eradicating weed populations, and rather should be part of an integrated pest management (IPM) plan. Even after targeted plants are reduced to desired levels, grazing, and browsing may be continued, perhaps at altered frequency and intensity, to maintain the ecosystem in the desired condition.

Although livestock production is compatible with habitat enhancement, there may be a production cost associated with targeted grazing. A land manager can usually expect to pay for a targeted grazing service. In contrast, when grazing supports livestock production, the rancher typically pays to graze.

Access and infrastructure (roads, fencing, gates, and water) may limit the ability to use grazing on a given site. Truck and trailer access for example may be required to transport animals. A legal perimeter fence must have five strands of barbed wire, while a single strand of temporary electric fence may suffice for an interior fence. The grazing operator can determine if the fences in the area are sufficient. The ability of grazing and browsing to control vegetation is not hindered by distance from roads as much as it is limited by logistics related to grazing. Facilities for handling livestock are another consideration. At a minimum, a loading chute is required. This could be a small pen with panels to funnel animals into and out of a trailer. In general, larger livestock require more infrastructure than smaller livestock. In every grazing area fresh water from either a stock pond, trough, or stream must be accessible to the livestock. Water, salt, or other supplements may be used to attract livestock to target plants.

Grazing and subsequent digestion by animals will not kill all seeds. Seeds can remain viable and can be spread to other areas or distributed further in the control area if sufficient care is not taken in animal management. Thus, grazing must be done prior to seed set, preferably right as the plant is leaving the vegetative stage and entering the reproductive stage (full emergence of seedhead). Timing varies for each plant and can vary year to year depending on precipitation and temperatures. Grazing at this time capitalizes on higher plant palatability compared to later reproductive stages when seeds are developed, while occurring late enough in the year for annual plants to be moisture limited and not able to regrow. Grazing before this time may allow the plants to recover and flower before the season ends.

Moist soils are more susceptible to compaction than dry soils, so high-density grazing may compact soils more during wet conditions. Managers should consider the risks of compacting soils on desirable species when considering using high animal densities or prolonged periods of grazing during wet periods.

Livestock grazing has been used in recreational use areas. Even when managers educate park users on the use of livestock in the park, common management practices, and how to share the trails (such as no dogs off leash), ranchers in these areas must deal with open gates, trash around the trails, and other nuisances. While these may seem minor, gates are important in targeted grazing, keeping animals in or out of a specific area to remove weeds. Livestock may try to consume trash found along trails creating an animal health concern.

If there are bighorn sheep in the area, care should be taken when planning sheep or goat grazing. Domestic sheep have been found to carry respiratory diseases that have a higher mortality rate in bighorn sheep. Results are mixed regarding goats also being carriers and may depend on whether the goats have been mixed with domestic sheep or not (Pils, 2018).

Potential Hazards to Humans, Environment, and Cultural Resources

Human safety. Low risk. Human hazards and conflicts are rare with livestock grazing. If using animals in an area where there is recreation, there can be perceived potential hazards from the public, especially if visitors have off-leash dogs. Dogs off leash around cows with calves create a potential issue since the cow will protect her calf from her perceived threat of the dog or even the person if they are too close. Sheep and goats will not seem as threatening to people because of their smaller size but will still protect their young as will the guardian animal with them. University of California Cooperative Extension efforts to educate users on natural animal behaviors and how to share space (such as restricting dog use or enforcing leashed dogs only) have reduced conflicts (fact sheets are available: https://ucanr.edu/sites/BayAreaRangeland/). Grazing and recreation co-exist in East Bay Regional Parks in the San Francisco Bay area, Sonoma County Open Space, East Bay Municipal Utility District lands and San Diego County Parks, and other areas.

Cultural resources. Low risk. Livestock grazing typically is not a concern regarding cultural resources. If there is concern about potential trampling or soil erosion at cultural resources sites, the site can be fenced off with temporary electric fence.

Sensitive species. Low risk. Livestock grazing typically is not a threat for most sensitive species. Grazing in vernal pools, once thought to be detrimental, has since been shown to be beneficial to vernal pool flora and fauna. Many threatened and endangered species live on rangelands, some of the last habitat available to them due to surrounding development of natural areas for housing, vineyards, and orchards. In many cases, invasive species are more detrimental to habitat than grazing. Woody species in grazing areas may be a concern, but grazing can and should be controlled to balance weed management with browsing on woody species and soil moisture. Win-win situations are possible, and monitoring should be done to ensure goals are met.

Erosion risk. Low (with proper management). Erosion risk is minimal for most habitat types when grazing is properly managed. Established residual dry matter (RDM) guidelines related to rangeland type and topography are available at https://anrcatalog.ucanr.edu/pdf/8092.pdf. Although the RDM publication focuses on productivity, the guidelines also help protect soil from erosion and nutrient loss. Riparian or wetland areas grazed in the wet season would be at the biggest risk of erosion. Time grazing, if possible, to the dry season when there is less soil moisture.

Other Non-Chemical Methods to Combine With

Grazing is compatible with other methods in an Integrated Pest Management (IPM) plan. Grazing may be followed-up with other methods of control when control is incomplete, and it may also supplement other control options. It can be included in any plan to remove woody species since young growth is very palatable and grazing can lengthen the lifespan of the results of mechanical removal or a controlled burn. Grazing can be a viable alternative to mowing as well. Multispecies grazing, using cattle, sheep, and/or goats at the same time, should also be considered where appropriate.

When Not to Use

Do not allow grazers to feed on toxic plants. Many plants can be toxic to animals. Below is a table of common plants found on rangelands that are known to be toxic to livestock. It is not comprehensive.

While some of the plants listed are often grazed successfully (ryegrass, starthistle), often there is a timing or amount of the vegetation that provides a safer grazing window. The list below is from *Livestock-Poisoning Plants of California*, 2011 (see References). An "X" means the plant does have toxic characteristics for that species. Note that this is not a comprehensive list of toxic plants.

Plant (common name)	Cattle	Sheep	Goats
Arrowgrass	X	X	X
Avocado			X
Chokecherry	X	X	X
Cocklebur	X	X	X
Curly Dock	X	X	
Deathcamas	X	X	X
Dogbane/Indian Hemp	X	X	X
Fiddleneck	X	X	X
Foxtails	X	X	X
Greasewood	X	X	X
Groundsel	X	X	
Horsetail	X	X	
Klamathweed	X	X	X
Tall Larkspur	X	X	
Locoweed	X	X	X
Lupine	X	X	X
Milkweed	X	X	X
Nightshades	X	X	X
Oak	X	X	X
Oleander	X	X	X
Poison Hemlock	X	X	X
Ponderosa Pine	X	X	
Ryegrass	X	X	X
Starthistle		X	
Summer Pheasant's eye	X	X	
Tobacco	X	X	
Toyon	X	X	X
Veratrum	X	X	
Water Hemlock	X	X	X
Western Bracken fern	X		

The importance of timing and stocking rate are critical when managing species with lower palatability. Both yellow starthistle and medusahead can be reduced with properly timed grazing at appropriate stocking rates but can increase if too few animals are used, and they are able to selectively graze more palatable species or if implemented at the wrong time.

Photographs

Cattle grazing in an oak woodland/grassland ecosystem. Photo credit: Theresa Becchetti.

Sheep waiting patiently for better forage. Photo credit: Theresa Becchetti.

Targeted weed and thatch grazing, before and after. Note some foliage damage on shrub. Photo credit: Robert Freese.

Targeted browsing of Himalayan blackberry with goats. Photo credit: Mark Horney.

Left: Goats used for fuel modification along a firebreak. Photo credit: Mark Horney. Water provisioning at a remote grazing site. Photo credit: Theresa Becchetti.

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Supplementary Information

History

Grazing and browsing animals have roamed California's landscapes for millions of years. Although the large grazing herds of bison found in the Midwest never occurred here, large herbivores did populate the grasslands, shrublands, and woodlands during the Pleistocene. The arrival of the first humans at least 20,000 years ago coincided with the mass extinction of many species of megafauna. However, it was the arrival of Europeans and domestic livestock in the 18th century that began the transformation of California's landscape. Non-native grasses and forbs spread throughout California's coastal prairies, valleys, deserts, and foothills.

Burcham (1961) described how California coastal and central valley rangelands were converted to annual grasslands. That began with the first establishment of permanent Spanish settlements in the mid-late 1700s, which led to the incidental introduction of Mediterranean grasses and forbs. The spread of those plants seemed gradual until the 25-year period from 1845 to 1870 in which a rush of livestock into California with the Gold Rush, followed by a historically severe drought, and then widespread plowing of grasslands for wheat production decimated many native grass populations. During the Gold Rush, the human population, surging from 26,000 to 380,000 from 1849-1860, generated massive increases in demand for food (Jelinek, 1999). In that decade, cattle numbers grew from 250,000 in 1850 to one million by 1860 (Stewart, 1936). The first California sheep census in 1850 found 17,514 animals remaining, compared to the 17 million estimated in 1825. Sheep were rushed into California from nearby states during that period. A half-million came from New Mexico alone between 1852 and 1870. By the mid-1870s, California sheep numbers had recovered to 6 million (Miller, 1930). Now, grazing of domestic livestock is a widespread use in California, with up to 40% of California being grazed each year. According to Saitone (2018), beef cow numbers, which are the primary type of livestock grazing on California's grazing lands, peaked in 1982 at nearly 1.2 million head. In January 2020, the state livestock inventory listed 665,000 beef cows; 570,000 sheep (including lambs); and 87,000 meat & other goats (NASS, 2020).

Developing a Grazing Prescription

Grazing is simply a means of removing biomass that is like mowing or burning. A management prescription to conduct grazing is important to optimize grazing to achieve your objectives while minimizing environmental risk. It can only be as good as the data which informs it. A prescription begins with clear and specific objectives for the activity.

Example:

We will use cattle here for the numbers, but you may substitute any species by using the Animal Unit equivalent (AU), the weight of an animal in relation to 1,000 pounds. A 200-pound sheep, for example, would count as 0.2 AU (200lb ÷ 1000lb = 0.2).

Suppose a local fuels management specialist advises managing for not more than 1,000 pounds per acre (lbs/ac) fine fuel that blends into brush on a 1,200-acre hillslope opposite a residential area based on UC recommendations for RDM. The site typically produces an average of 2,100 lbs/ac, with peak production normally reached between March 1 and April 15 (Ecological Site Description; Fig. 1). The local NRCS soil conservationist recommends managing for not less than 800 lbs/ac residues on the hillslopes to guard against soil erosion. Your consulting CRM recommends estimating a 7%/month residue decay rate between June 1 and November 1 (5 months; the optimistically estimated return of germinating fall rains; Fig. 2). That works out to a minimum of 756 lbs/ac of residues that needs to be left on the ground on June 1 (assuming no further grazing after that time). That gives about 30 days of grazing at higher grazing pressures, or several months of grazing at lower grazing pressures.

Math:

If a couple neighboring ranches offer to graze that hillside, and it was covered mostly in vegetation that the cows would eat, how many cows would it take to do the job in 45 days (March 1-April 15)?

To figure that out, we would start with the best data we had on grassland productivity for that site. If no actual measurement data is available, we could go to the USDA-NRCS soil survey or an Ecological Site Description for the area (if one exists). Let us say a local conservation organization has been monitoring grassland productivity nearby, and their data indicates an average of 2,100 lbs/acre.

Can you just ask the ranchers to take all the vegetation off this hillslope to make it extra safe for the homeowners on the other side? That would likely create a crisis for many wildlife species and native plants, not to mention probably lead to significant soil erosion. So, take the NRCS conservationist's advice and leave 800 lbs/ac in place at the time the fall rains normally begin. That means you can graze it down to 800 lbs/ac on April 15, and leave the dead grass until November? No. The dead grass decays – even in summer. The University of California Cooperative Extension conducted research in Kern County that found the decay rate there was about 7% per month. Probably that varies, depending on location and moisture levels. But we will assume using that should be adequate here. If we need 800 lbs/ac on the ground November 1, and it decays at a rate of 7% per month (we assume), how much should there be on April 15? To do that we will multiply the November 1 RDM objective (800 lbs/ac) by (1+7%) raised to the 6.5 months to get us to November 1. That gets us to 1,242 lbs/ac.

Now we can figure out how much there is for the cattle to eat. If the total amount is 2,100 lbs/ac, and we must leave 1,242 lbs/ac behind, that leaves us with 858 lbs/ac that is grazable. There we go, right?

Nope. Turns out that when you let animals walk through their food, they trample and poop on about as much as they actually eat. So, we plan to use 50% of that (called "harvest efficiency" by the USDA-NRCS). That gets us to 429 lbs/ac. That times 1,200 acres gives us 514,864 total pounds of forage that the cattle could remove by eating.

Last steps. Let us say the ranchers say their cows average about 1,300 lbs in weight. Using an intake estimate of 2.6%[1] of body weight for these animals, that gets us 33.8 lbs/cow/day. If we are giving ourselves 45 days to get this job done, how many cows would it take? That will be the total amount of consumable forage (514,864 lbs) divided by the daily intake per cow (33.8) times the number of days (45). That gives 339 cows.

This probably already seems fairly complicated, but it is a relatively simple problem as grazing projects go. And we have simplified a number of things in it (not least, if cattle are only actually eating half of what remains in the field, why didn't we just roll that back into the RDM objective?). These are examples of things for which it is useful to seek the advice of local specialists. For large projects, professionals like CRMs make sense and can be worth the extra expense. For smaller projects, UCCE and staff from conservation organizations can be sufficiently helpful as well as most reputable grazing managers. Grazing managers (ranchers) calculate the feed available for livestock on a regular basis.

Also keep in mind that members of the ranching community who consistently employ good management practices (and there are many of them) provide substantial community benefits by managing their lands in ways that minimize fire hazards while also maintaining habitats for wildlife and native plants. Their fuel management on their own lands, through grazing, brush management, and (in some areas of the state) prescribed burns, protects not only them, but others to whom fires passing through their properties could potentially spread.

[1]The US Animal Unit Month (AUM) system assumes an average annual forage consumption rate of 2.6% of live weight for mature cows. The actual consumption rate can vary from as low as 1.5% (losing weight in the dormant season) to as high as 3.5% (lactating on fresh, abundant grass).

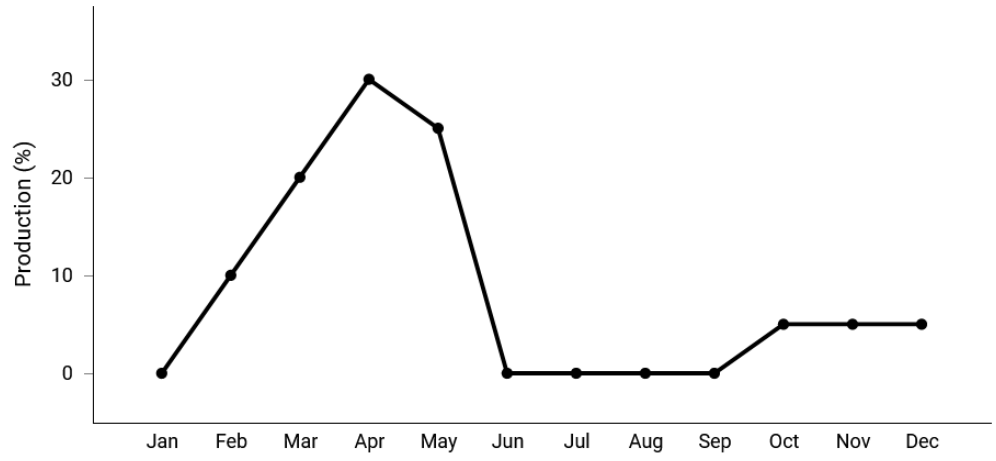

Figure 1. Ecological Site Forage Production Report

Decay rate:	3.5%	per 2 wk period			
		Minimum			
	Residue	Pasture			
Date	Objective	Biomass			
	lbs/ac	lbs/ac			
1-Dec			"Compound Interest" formula:		
15-Nov					
1-Nov	800				
15-Oct		828	=B9*(1+B$1)^1		
1-Oct		857	=C10*(1+B$1)^1		
15-Sep		887			
1-Sep		918	•		
15-Aug		950	•		
1-Aug		983			
15-Jul		1,018	•		
1-Jul		1,053			
15-Jun		1,090	End of seasonal growth		
1-Jun		1,128	1,251	=B9*(1+B$1)^10	
15-May		1,168			
1-May		1,209			
15-Apr		1,251			
1-Apr		1,295			
12	2 wk periods				

Figure 2. RDM (residue) Decay Rate Adjustment

Classes Livestock

Cattle. A cow-calf pair is a cow (female) with her calf up until she weans her calf at roughly eight to nine months. A dry cow is a cow who is no longer nursing her calf, from when the calf was weaned until she has her next calf. A stocker or yearling is a weaned calf (heifer- female; steer- castrated male) up to two years of age. Typically, in California stockers are shipped into the state roughly in November, and graze for one more growing season. Bulls are the males, and most ranches only have the bulls with the cows during the breeding season, ranging from November to possibly March for fall calves as part of a normal husbandry practice. Cow-calf pairs are the most common type of livestock grazing in California. Calves and stockers are typically removed from California's grasslands when forage does not provide adequate nutrition to support growth.

Sheep. Sheep have a different production cycle than cattle, a shorter gestation length, shorter period they nurse their lambs, and a smaller window to be bred. Terminology for sheep will be ewes (mature females), lambs (babies), wethers (castrated males) and rams or bucks (mature, intact males). Ewes tend to have twins more often than singles, and it is not uncommon to have triplets.

Goats. Goats are like sheep in terms of having a short production cycle, typically having twins, and requiring protection from predators. Terminology changes to nanny goats, kids, and billy goats, and wether is still used. Many breeds used for contract grazing have horns (Spanish, kiko as examples). Wethers are more often used for contract grazing than breeding flocks.

5.4 Mechanized Tillage

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Overview

Tillage involves purposely disturbing the soil to sever, chop, bury or desiccate weeds. This occurs most often on large scales by large mechanized agricultural equipment but can be conducted at smaller scales with mechanized push equipment as well. The terms tillage and cultivation and are often used interchangeably when referring to a method of controlling weeds through soil disturbance with a mechanical implement.

Tillage is most common in agricultural settings but can also be used in rangelands and other non-crop areas. Historically tillage equipment was pulled by draft animals, but most modern tillage is accomplished with mechanized equipment (tractors, off-road vehicles, or mechanized push equipment). This document is specific to mechanized tillage. The use of hand tools to sever weeds in the soil is covered in the Grubbing with Hoes and Scuffle Hoeing BMP sections.

Tillage has been a method of controlling weeds in agriculture for millennia, and a variety of tools have been developed to aid in reducing weeds. Implements commonly used for tillage include cultivators, harrows, and plows, alone or in combination. If a land manager does not have access to large agricultural equipment, smaller tillage options include a rototiller or dragging implements behind an off-road vehicle (ORV). Tillage equipment should always be thoroughly washed before and after working on a new site to prevent unwanted dispersal of weed seeds or propagules.

Tillage is a non-selective form of weed control that causes extensive soil disturbance. It can be used to prepare sites for the establishment of desirable species through active revegetation.

How to Use

Effective tillage for weed control involves dragging metal blades and/or tines through the soil, usually pulled by a tractor. The depth and shape of the blade or tines vary with the type of soil, whether the soil is to be turned over (thus burying the weeds), or if the blade just severs the weeds underground. The types of weeds, slope, soil type, soil depth and moisture content will determine which implements to use.

The main categories of mechanized tillage equipment used for weed control include cultivators, harrows, and plows, each with several variations. Many have local names or are referred to by manufacturer name, which can be confusing to non-experts. Cultivators include equipment with tines (sometimes called teeth or shanks) that are dragged through the soil, or equipment that uses rotary motion of discs to uproot or bury weeds and weed seed. Cultivators generally only disturb linear trails and not the entire soil surface, as they were designed to till soil on either side of a row of a planted crop.

Plows use blades to turn over soil layers, creating furrows and burying weeds and weed seed. Plows (e.g., chisel plow or soil ripper) usually created the deepest soil disturbance. Harrows use blades (e.g., disc harrow), tines, or chains to create a shallow soil disturbance relative to plows but cover the entire soil surface as opposed to cultivators.

Tilling is most efficient on large, flat areas with friable soils lacking clods or stones, with relatively uniform weed infestations. Often sites need to have low or reduced residual vegetation to avoid clogging or breaking the equipment, especially when using rotary tillers. This is not necessarily true for deep ripping with heavy tines or plowing non-woody vegetation. Tillage in steeply sloped areas is not advised because of high safety risk and erosion risk.

When using large equipment, good road access is crucial so that the equipment may be off-loaded from trailers used for transport. That said, if tillage equipment is mounted on a three-point hitch and can be elevated above the soil surface and vegetation, a tractor can drive for miles to reach control sites once off-loaded. In more remote settings or areas with more difficult access tillage implements are pulled/propelled with ORVs.

Larger implements are more efficient because more soil can be tilled with a single pass of machinery. Width of implements can vary greatly from 20 to 60 feet wide field cultivators to single row cultivators with wings a few inches wide.

Control is most easily achieved for annual weeds that do not resprout when buried by turning over soil layers. Repeated tillage in consecutive years is often required for successful weed control. Tillage is best used at a time of year when the soil is not so dry that wind erosion is a concern, but not excessively wet so that damage to soil structure is a risk. Furthermore, proper soil moisture is critical for implements to be able to penetrate the soil, working the ground appropriately. Hard dry soil may not be effectively penetrated with tilling implements.

Depth of tillage will depend on the size of the weeds. Weeds in the seedling stage can be tilled at a depth of a few inches. This can be done with a drag harrow, or in some cases by dragging objects such as bundles of old tires, or chain link fencing using a pickup truck, ATV or UTV. When using modified (non-agricultural) equipment several passes may be necessary to adequately control the seedling weeds (this can also be true for a traditional disc harrow). Dragging these sorts of implements will disturb the soil surface and uproot seedling plants, while minimizing soil disturbance compared to deeper tillage with other implements. Weeds that are well established may need to be tilled at a depth of several to many inches to sever the stem below the soil surface. Larger perennial weeds may need to be deeply plowed with a chisel plow or ripper at a depth of 8 in. to greater than a foot. Do not till perennial plants with rhizomatous roots, as tillage can break up the roots into smaller pieces, spreading patches throughout the field.

Tilling is indiscriminate and cannot be used selectively when weeds are intermixed with desirable vegetation. Tractors can drive around established native perennials or patches of annuals when cover is low or patchy. If desirable vegetation cover is high, tillage should not be used unless removing desirable species is considered acceptable. Smaller equipment such as ATVs/UTVs can be more selective because they can be steered around nontarget vegetation more easily.

Tilling can be used to selectively remove weeds growing at different seasons. For example, winter annual weeds (e.g., wild oats *Avena* spp., bromes *Bromus* spp., or storkbills *Erodium* spp.) can be tilled from fall through winter if desirable spring or summer annuals, especially those that thrive in disturbed soils (e.g., doveweed, *Croton setiger*, or tarweeds, *Deinandra* spp.) are planted later in the growing season. Depending on precipitation, soil moisture, temperatures, and other factors, multiple flushes of weed seedlings may emerge which will require multiple tillage events.

Repeated tilling is often used to flush the weed seed bank by bringing more deeply buried seeds or propagules closer to the soil surface. These seeds will sprout and can be killed with a repeated tilling or other treatment. Additionally, when invasive species have built up a shallow seedbank, tillage utilizing an implement such as a moldboard plow can invert the soil deeply burying that shallow seedbank. This type of tillage can only take place in deep non rocky soils and may require active revegetation of desirable species following the treatment.

Utilization of competitive planting is almost always necessary following tillage for invasive weed control. The soil disturbance associated with tillage can promote new or increased weed invasion on site and may be harmful over the long term if disturbed soils are not actively revegetated. Many weed species present in California thrive in disturbed soils and tillage will promote ruderal species colonization and development on site. Species such as tumbleweed (*Salsola* spp.), invasive annual grasses (non-native *Hordeum* spp., *Avena* spp., and *Bromus* spp., among others), field bindweed (*Convolvulus arvensis*) or hairy fleabane (*Erigeron bonariensis*) all thrive in disturbed soils. Without additional management of these weeds, land managers may face a problem worse than initially found on the site. On the other hand, tilling is one of the few non-chemical weed control methods that can be highly effective for killing weeds uniformly in heavily infested fields (From small to large and very large sites, over 100 or even 1,000 ac.).

Tilling may not result in eradication of a weed species from a site and is usually best used in combination with other techniques as part of an integrated weed management strategy. As a standalone technique, tillage can be effective for local eradication under the following conditions:

1) The target population is limited to flat ground and accessible by road.

2) There are no cultural resources present that are sensitive to soil disturbance.

3) There are no sensitive species interspersed among the target invasive population.

4) The soil can be deeply tilled if perennials with extensive root systems or underground reproductive structures are present.

5) Repeated tillage (multiple times per year) is possible to address the soil seed bank and to control plants that are missed.

Some important caveats exist for the last two points. First, tillage is generally not recommended for perennial species unless the entire plant can reliably be uprooted and left to desiccate on the soil surface (rooting depth and rooting system are important considerations). Second, repeated tillage can be very expensive and is associated with accelerated soil erosion.

Tillage will require expensive machinery and managers should budget not only for operation but also for maintenance, depreciation, transportation, and fuel. The method itself is costly but can be cost effective at large scales or for repeated treatments. Associated restoration costs may be inevitable and costly due to the disturbance of the area.

Special Tips

Shallow tillage can be achieved via equipment like a flexible tine harrow, rotary hoe, or Perfecta® cultivator. This is useful to avoid disturbing deeply buried weed seed or perennial structures like tubers of desirable species. Deeper tillage can be achieved using equipment with strong tines (rippers and chisels) that can be a foot or more in length. This can be useful for uprooting shrub and tree species or severing deep roots. Often these larger tines are attached to equipment with tracks and require substantial of power to drag the implement through the soil. Utilization of these deep implements can be useful for breaking up soil in heavily compacted areas such as restoration of old roads.

Another modification of this technique is chaining. Chaining is most typically used on rangelands where the cover of woody species is above target levels. In this technique a long piece of marine anchor chain is dragged on the ground between two tractors, or in a large circle with one tractor. Chaining will disturb the soil and uproot or break the stem of woody weeds. This technique is best used on woody weeds that do not resprout. If woody weeds can resprout, the improvements will only last several years and will need additional treatments to reduce the surviving woody plants. Often herbaceous vegetation will be only moderately damaged by the chain and will quickly recover on the site. As with all tilling, soil disturbance and erosion following chaining could be significant.

Some farmers who practice organic agriculture or conservation tillage are developing tilling methods that greatly reduce weed populations and, in some cases, reduce soil disturbance too. These methods can vary from using various plow types in novel ways to detailed timing of tilling. These methods are not discussed in this document, but land managers are encouraged to contact their local experts to learn more about methods that may be adapted to wildlands.

Optimal Conditions for Use

Weeds are best tilled when small and optimally at the seedling stage. Terrain should consist of large, flat areas, and soils should be in a condition that can be easily worked. Annual and biennial plants are easily controlled with tillage, but it is important to till before plants produce fruits or underground storage structures (bulbs, tubers rhizomes, etc.) as tilling can exacerbate weed issues by spreading propagules. Perennial species can be controlled well with tillage if used during the summer months when conditions are hot and dry and perennial underground structures can be brought to the soil surface to desiccate and die. (This is only effective for perennials with shallow and discrete root systems.) Under cooler or moister conditions, tillage may be counterproductive by cutting up the perennial underground structures and spreading these vegetative propagules throughout the area, exacerbating the problem. Small shrubs, tree seedlings, and vines may be effectively controlled if tillage is performed during summer months under hot and dry conditions.

Caveats

Tillage requires the use of mechanized equipment, and in some cases this equipment is expensive and requires specially trained operators. Tillage can result in short-term control of certain weeds but can also exacerbate weed problems in the absence of repeated treatments. In this case an integrated weed management strategy or a restoration plan is necessary. Repeated tillage can shift vegetation composition toward the dominance of more disturbance-adapted species, which are often invasive weeds, and less diverse plant communities. Tillage may exacerbate spread of perennial grass weeds and those with underground storage structures but provides excellent control of annuals.

Potential Hazards to Humans, Environment, and Cultural Resources

Human hazards. Moderate risk. All vehicles, heavy machinery, and cutting equipment incurs direct risk of human injury. Internal combustion engines typically use petroleum products that generate chemicals known to have acute and chronic risks from exposure.

Habitat. High risk. Tillage disrupts the soil surface and soil structure. It has very high impact to undisturbed habitat.

Sensitive species. High risk. Ground nesting birds and burrowing animals are particularly susceptible to mortality or injury from tillage. Tillage should be performed outside of the breeding season for birds or avoided altogether when burrowing animals that are priorities for conservation are present. Slow moving animals like reptiles, amphibians, turtles, and tortoises cannot outrun tillage machinery and are also at risk. Juveniles of species such as deer may often hide in high weed cover so care should be taken to avoid tillage when juveniles of these species are known to be present.

Erosion. High risk. Tillage breaks the soil crust and removes vegetation that otherwise covers soil surfaces, leaving the surface highly vulnerable to erosion from wind and rainfall. Silt fences should be employed wherever tillage is used next to streams or other waterways, or where there is undisturbed habitat downslope.

Cultural. High risk. Tillage should not be used in areas where cultural resources are present unless under supervision of the appropriate regulatory jurisdiction or agency.

Other Non-Chemical Methods to Combine With

The flush of seedlings following the soil disturbance from tillage can be controlled with other tools, such as flaming or solarization for smaller-scale control efforts. Mowing can be employed to reduce seed production of target weeds while maintaining vegetative cover and minimizing erosion.

Tillage can be used in combination with other methods that first reduce residual vegetation. For example, livestock grazing or prescribed fire can be used before tillage to reduce vegetation which would otherwise clog or damage equipment.

Tillage can be used in conjunction with competitive planting. Tillage can be an excellent way to prepare a seedbed at a highly disturbed site by loosening soil while controlling non desirable species at the site. Often tillage is utilized in areas with large populations of non-desirable vegetation. Planting desirable

species into the areas which have been tilled is often necessary to shift the community to a more desirable plant community.

When Not to Use

Caution should be used when tilling any species that reproduces vegetatively. Tillage can be used effectively against such species under specific conditions, such as during hot and dry weather when underground reproductive structures can be brought to the soil surface to desiccate, though unintentional spread of propagules is still a concern.

Damage to soil structure is likely under moist conditions, so tillage cannot typically be used in marsh, wetland, or riparian settings.

Tillage can be used in shrubland, woodland, and forest areas (if spacing of woody species allows for access of mechanized equipment) but damage to nontarget species is likely.

Moderate to steep slopes should be avoided due to risk of vehicle rollover and erosion.

Tillage cannot be used under cobbly or rocky conditions.

Photographs

A 4x4 UTV pulling a modified harrow weighted down by an old tire as a winter seedbed treatment for a shrub restoration plot. Note that there is low residual plant cover and weeds are small. Photo credit: Ryan Lawler.

Drag spike-tooth tractor attachment. Photo credit: Kevin Nicholson.

Spring tooth harrow tractor attachment. Photo credit: Kevin Nicholson.

Ripper attachment. Photo credit: Kevin Nicholson.

Offset disk and tractor. Photo credit: Kevin Nicholson.

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Supplementary Information

In some wildland restoration projects tilling is used to control weeds on large-scale restoration plots of several hundred acres. For example, an entire field may be tilled to control the weeds, then planted with native trees in rows (at 8 ft. apart), maintaining a 2'-wide planting area and a 6'-wide tilling area to manage weeds throughout the growing season. Spacing between the rows can vary depending on the tractor width and the height of the native plants. If trying to establish large perennial shrubs or trees, the minimum row spacing will be the width of the tractor. If establishing shorter wildflowers or native grasses a variety of agricultural implements can be used to shape narrow bed widths.

In some areas, tillage may be used to add a soil disturbance that has been lost. For example, in some wind-blown sand dune habitats weeds dominate the soil surface and reduce sand movement. Tillage can break up the weed's roots and reduce soil structure to allow for the movement of sand on windy days. Careful planning is required to avoid stuck equipment, excessive erosion, and sand deposition on downwind properties.

6.Biological Control

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Overview

Classical biological control was first used in California in 1945 to control St. Johnswort, or Klamath weed (*Hypericum perforatum*) (Winston et al. 2012). Five species of insects were introduced, and within a decade the weed population was reduced by at least 97%. Today there are occasional 'outbreaks' of the weed, but the insects eventually colonize the patches and bring them back under control. A total of 77 agents have been released against 39 weed species in California, and 82% of the insects have established populations (Pitcairn 2018). This section addresses 22 target weeds that are most likely to be affected by existing biological control agents in California. These and additional species have been released in other states (Nechols et al. 1995, Van Driesche 2002, Coombs et al. 2004, Winston et al. 2014).

How it works. "Classical biological control" involves the use of naturally occurring host-specific insects, mites, or pathogens to help control invasive alien weeds (Smith 2007, Van Driesche et al. 2008, 2010, Smith et al. 2014). Although some insects or mites feed on many types of plants, most herbivorous species specialize on a limited number of plants to which they have adapted over evolutionary time. When a plant arrives in a new location that has a suitable environment and that lacks the herbivores or pathogens that normally attack the plant, it can multiply and become an invasive weed. The strategy of biological control is to find host-specific natural enemies (herbivores or pathogens) of the target weed in its region of origin and to release them in the invaded region to help reduce the weed's impact. Effective agents multiply and disperse, providing a self-sustaining population that helps to reduce the target weed. Often more than one biological control agent is needed before attaining satisfactory control of the target weed. Biological control does not aim to completely eliminate the target weed, and the level of control is likely to vary from year-to-year and among different types of habitats. However, the self-perpetuating reduction of the weed population can be highly cost-effective. For example, a comprehensive review of all programs in Australia, including those that failed to affect the weed target, reported a benefit to cost ratio of 23:1 (Page and Lacey 2006). Benefit ratios of projects around the world range from 8:1 to 7405:1 (van Wilgen *et al.* 2020). A recent review found that 61% of weeds targetted in North America have been effectively controlled (Schwarzländer *et al.* 2018).

Regulation. In order to not harm other plants, it is important to thoroughly test the host specificity of an agent before it is released. The USA has a well-established formal process for evaluating and approving new agents for release (Hinz et al. 2019). The Animal and Plant Health Inspection Service (APHIS) is a unit within the United States Department of Agriculture (USDA) that regulates the introduction and movement of organisms into and within the USA. APHIS formed the Technical Advisory Group for Biological Control Agents of Weeds (TAG), a committee that has representatives from all the federal agencies that have land management responsibilities, as well as from the National Plant Board, the Weed Science Society of America, and the departments of agriculture of Canada and Mexico. TAG reviews the scientific merit of petitions, in which everything that is known about the biology of the target weed and the prospective biological control agent is summarized. Petitions include a list of the species of plants tested, the results of host specificity experiments, and assessments of potential risks to

humans and the environment. TAG provides a recommendation to APHIS regarding the merits of the petition. Next, APHIS consults the US Fish and Wildlife Service (USFWS), regarding threatened and endangered species, as required by the Endangered Species Act. APHIS writes a Biological Assessment (BA) that documents possible risks to any threatened or endangered species. The USFWS reviews the BA and issues a Letter of Concurrence if they agree that the proposed action does not threaten any listed species. APHIS also consults with American Indian tribes. APHIS then prepares an Environmental Assessment (EA) that documents possible risks to the humans and environment, in compliance with the National Environmental Policy Act, which is published in the Federal Register to allow for a 30-day period to receive public comments. APHIS must respond to any comments received. If APHIS determines that there are no significant risks, it then signs a Finding of No Significant Impact (FONSI) before it can issue any release permits. This process can take several years or more to complete.

For a biological control organism that will be released in California for the first time, the California Department of Food and Agriculture (CDFA) requires a separate state permit after the federal permit is issued. CDFA will perform an independent analysis of the risk of the introduction and issue a state permit. California has many endemic plant species that do not occur in other states, so if any of them are at risk of injury by a prospective agent, the state would probably not issue a permit. Some weed biological control agents that APHIS has permitted for use in the USA are not permitted for release in California. Recently, APHIS has issued a "330 list of exempt organisms" which exempts many biological control organisms from the need for a federal permit to move them from one state to another. This rule is particularly helpful for commercial suppliers of biological control organisms who ship to several states. However, a State of California permit is required before moving one of these organisms into California, unless it has previously been approved by CDFA.

Safety. Because regulatory agencies have a low tolerance of risk to nontarget species, authorized biological control agents are highly specific and in general do not attack any nontarget plants. However, the oldest agents were evaluated under less stringent criteria and some of them feed on a few nontarget species. Such nontarget feeding is most likely to occur when the biological control agent populations are high (which may occur soon before the weed population shrinks) and the nontarget plants are near heavily infested target weeds. Such nontarget damage is usually transitory and ends after the target weed and biological control agent populations decrease. The species of plants most at risk of attack are often those most closely related to the target weed. A review of biological control in the USA reported that 15 (13%) of 112 introduced species of insect biological control agents attacked nontarget plants to some extent (Pemberton 2000). 40 of 41 plant species attacked were in the same or a very closely related genus of the target weed. The one exception was an insect introduced to Hawaii in 1912 that had never been tested. Most of the damage to nontarget species is transitory or inconsequential to their populations (Hinz et al. 2019). A worldwide review concluded that 99% of 512 species of biological control agents caused no significant nontarget attack (Suckling and Sforza 2014).

In the USA, the agent causing the most damage to nontargets is the thistle seed head weevil (*Rhinocyllus conicus*), which was introduced in 1969, at a time when there was little concern about protecting native plant species. This weevil has been reported to attack at least 22 species of native thistles in the USA, including causing significant damage to a federally threatened plant species (Pemberton 2000, Louda and O'Brien 2002, Hinz et al. 2019). Similarly, the thistle rosette weevil (Trichosirocalus horridus) was introduced in 1974 to control various exotic thistles (Cardueae), but it also attacks some native thistle

species (Takahashi et al. 2009, Wiggins et al. 2009). The cactus moth (*Cactoblastis cactorum*), which very successfully controlled invasive *Opuntia* cactus in Australia, was released on some Caribbean islands in 1957 (Zimmermann et al. 2000). It appeared on its own in southern Florida in 1989 attacking native *Opuntia* species and is spreading westward (Hight et al. 2002). Although this insect was never permitted for use in North America, this example shows how a natural enemy can be a safe and effective agent in one region, but a harmful invasive species in another.

It is important to understand the distinction between permitted agents and other adventive or accidentally introduced species that attack an invasive weed. The latter have not been evaluated for host plant specificity and may pose a threat to nontarget plant species. For example, the thistle seed head weevil (*Larinus carlinae* [often called *L. planus*]) has never been permitted in the USA but appeared in Maryland in the 1960s. However, it has a strong affinity with Canada thistle (*Cirsium arvense*) and was subsequently redistributed in some western states to control Canada thistle (Louda and O'Brien 2002). This weevil is known to attack at least 4 species of native thistles (*Cirsium* spp.), including a federally listed threatened species (Havens et al. 2012). Redistribution of this weevil has harmed some native species while having relatively little effect on controlling Canada thistle.

Land manager's role. Classical biological control is generally a "passive" technique of weed management in the sense that it works in the background, but a land manager can use their knowledge of how it works to apply other management strategies that are complementary. State and county personnel have released biological control agents (insects and pathogens) that have been officially authorized by state and federal regulatory authorities. If these agents are already present at your site, then there is probably no benefit to trying to obtain more to release because the number that you would release (dozens) is small compared to what is already in the field (thousands). However, it is useful to know if there are agents at your site and to observe how abundant they are to help you select other management strategies that complement their effect. Steps taken to protect the insects will help increase their impact in successive years. It is important to understand that agents are living organisms, and that their populations will increase from year to year unless something is causing them to die or fail to reproduce. Biological control is generally a slow process, but it can be effective over very wide regions and perpetuates year after year.

Tips for using biological control agents. Obtain insects from CDFA, the local county agricultural commissioner or from field sites that have established agents. Some agents may be available from commercial vendors.

In general, biological control agents will multiply if they have a suitable habitat and are protected from disruptions (e.g., fire, herbicides, mowing). Undisturbed sites are more likely to allow populations to increase year after year.

Species of biological control agents differ in their life cycles and their habitat and environmental preferences. Knowing these details will help land managers to choose which species are most likely to be useful at each site, and to understand where they are likely to establish and have the greatest effect.

After agents become established at a site and their populations increase, they can be collected for redistribution to other sites. This is best done before the weed population decreases because after it decreases, the populations of biological control agents will also decrease.

Knowing that biological control agents are present may help you to integrate other management strategies. For example, it would be better to use a treatment such as herbicides or other non-chemical methods to control the periphery of a weed infestation and at 'high value' sites and let the biological control agents multiply in the center of the weed infestation. Over time, the agents should reduce the weed density to acceptable levels, and/or enable more efficacious use of other treatments such as herbicide, mowing, or fire.

Treatments that kill the target weed during the time of year that the biological control agent is on the plant are likely to reduce the agent's population and efficacy. Thus, it is worth considering treating plants **before** the agent is active, in which case the agent will seek out plants in areas that were not treated (e.g., too difficult to access, or in sensitive areas). Alternatively, treating **after** the agent is active might be an option, although this time of year is usually less efficacious for herbicides, mowing, or fire.

Any treatment regime, whether biological, chemical, or otherwise, should include revegetation with native or other desirable plants to promote competition by desirable plants. Competition stresses weeds and increases the impact of other treatments, including biological control agents.

Caveats. Application of insecticides at or near the site (e.g., to control mosquitoes or crop pests) will likely kill the biological control agents if adults or externally feeding larvae are active at the time of application.

Classical biological control can help reduce densities of the target weed, but it is not expected to completely eradicate it. Furthermore, the weed population may fluctuate from year to year, and location to location, but persistence of the biological control agents will help to prevent it from increasing to injurious levels.

Permits. A federal (USDA-APHIS) permit is required to introduce an agent from a foreign country or to move it from one state to another. Apply for a federal permit (PPQ form 526) at: www.aphis.usda.gov. A state (CDFA) permit is required for the first time an agent is introduced into California. Agents brought from other states would need a state permit only if they have not previously been approved by CDFA. The list of approved agents can be found in Pitcairn et al. (2014). Apply for a state permit (Form 66-026) at www.cdfa.ca.gov and email permits@cdfa.ca.gov regarding questions. Once a permitted weed biocontrol agent is established, CDFA generally does not require a permit to collect and move it within California. However, contact CDFA first to verify this for the agent in question. For example, the Dalmatian toadflax stem weevil (*Mecinus janthiniformis*) can only be released in southern California. Permission of the landowner should be obtained before collecting or releasing agents on their property.

Field methods. A variety of methods can be used to collect insects or pathogens. Choose the methods that are most appropriate for the species of interest. For more details, see the US Forest Service FHTET publication that is listed in the references of the section on the weed target of interest. Specialized equipment can be obtained from entomological, forestry or scientific vendors such as Bioquip.com.

Aspirators are used to collect insects into a vial or tube by suction. They are most effective for insects that are small and not actively trying to fly. The suction can be applied orally or by battery power depending on the model. Oral models should include a filter to protect the user from inhaling dust or insect scales.

Beating involves hitting vegetation with a stick to knock off insects that fall into a sweep net or horizontally held sheet. The desired insects are then collected by aspirator or small container.

Sweep nets are used to collect adults and some external leaf-feeding insect larvae. A sweep net consists of a conical cloth or mesh bag attached by a hoop to a long handle. Sweep the net from side to side hitting the vegetation (target weed) to dislodge insects so that they fall into the net. Roll the handle 180° to momentarily close the bag. Insects tend to move upward and are attracted to light, which can help to separate them from the debris. Collect the desired species using a small container or aspirator. Immediately release other insect species that you do not want because they may include beneficial native species. Note that this method may injure delicate species (moths and flies).

Night collecting sheets consist of a white cloth that is suspended vertically and illuminated with a white or black light to attract flying insects at night. The desired species are collected from the sheet by aspirator or small container.

Transferring infested plants or plant parts. Insects that spend the winter inside seedheads or galls can be transferred by collecting mature seedheads or galls late in the season and putting them at release sites. It may be necessary to protect them from rodents and birds by placing them inside a metal cage. For agents that are known to have parasitoids, it is better to hold the seedheads or galls in a rearing chamber to rear out the adults and release only the correct species and not move the parasitoids to the release site.

Storing, transporting and releasing agents. Most insects tolerate cold (refrigerator) temperatures well, whereas they often die quickly when confined in warm containers. Most insects are inactive at temperatures lower than 50°F, which is helpful for storing and handling them. Avoid overcrowding insects and put cut strips of paper towel or host plant vegetation in the container to provide them places to hide. Allow ventilation and avoid creating condensation droplets inside containers because insects can get trapped and drown in the liquid water droplets. Cardboard 'ice cream' containers (unwaxed) are often used. Hold the insect containers in a refrigerator or a cooler with blue ice until ready for release. Avoid releasing insects at midday during hot weather and place them directly on the target weed to encourage them to settle rather than immediately fly away.

New targets. The development of a new biological control agent is expensive and involves many years of research to discover, identify, test, obtain permits, multiply, and release. Investment to develop biological control differs significantly from that to develop chemical or mechanical methods of control because an individual investor cannot 'monopolize' or capture the profit from their investment. When an agent is released on someone's property, there is nothing to prevent it from eventually dispersing to their neighbors, who would benefit from the initial release. Thus, there is little motivation for an individual or private corporation to invest in classical biological control; however, the high benefit-to-cost ratio of classical biological control makes it a very attractive investment for society as a whole. Projects are usually supported with public funds at the federal, state or county levels. Perhaps the most effective role that weed managers can play is to inform their government representatives of the importance of their weed targets and the need to support research and development of solutions.

Although classical biological control can be highly effective to achieve long-term control of an invasive weed over a wide region, it is not a suitable strategy for all weed targets. Projects involve a large investment and require many years to achieve results, so the target weed should be important enough

to justify this. For recently established invasive weeds, it may be more realistic to target them for eradication and containment. Typically, weeds that have become widespread and that cannot be cost-effectively controlled by other methods are targeted for biological control. Thus, biological control is often a tool of 'last resort.' If the target weed has close relatives that are native or cultivated species, then it is less likely that an agent that is sufficiently host-specific can be found. However, modern molecular genetic tools are greatly increasing our ability to understand the genetic variation of both the target plants and the prospective biological control agents, which is improving our ability to discover new prospective agents.

Commercial vendors. We know of only two suppliers of weed biocontrol agents that ship to California:

Integrated Weed Control
4027 Bridger Canyon
Bozeman, MT 59715-8433
email: IWC@integratedweedcontrol.com
Web site: integratedweedcontrol.com
They sell agents for: Canada thistle, knapweeds, purple loosestrife, St. Johnswort.

Weed Busters Biocontrol
5607 Hillview Way,
Missoula, MT 59803
(406) 251-4261
email: RobertKandace5@msn.com
Web site: weedbustersbiocontrol.com
They sell agents for: Canada thistle, leafy spurge, spotted and diffuse knapweed.

Mention of company names, trades names or specific commercial products is solely for the purpose of providing specific information and does not constitute endorsement by the U.S. Department of Agriculture (USDA) or the California Department of Food and Agriculture. The USDA prohibits discrimination in all its programs and activities on the basis of race, color, national origin, sex, religion, age, disability, political beliefs, sexual orientation, or marital or family status. Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD).

Glossary

accidental introduction — species that appear in a new region (e.g., California) that were not authorized by the appropriate regulatory agencies. This applies to many non-native weeds, but also to some of their natural enemies. Such species are not authorized for use to control invasive plants because they have not been evaluated for safety and potential risks.

adventive — unpermitted non-native species that arrived by unknown means.

APHIS — Animal and Plant Health Inspection Service is the branch of the US Department of Agriculture that is responsible for regulating the movement of live organisms from other countries to the USA, and between states within the USA.

BA — Biological Assessment, a document that assesses the risk of a proposed action on threatened and endangered species. This is in compliance with the Endangered Species Act of 1973.

biological control — This term is sometimes broadly interpreted to include use of targeted grazing, botanical pesticides, and genetic methods; however, in this document we intend for it to refer to use of living organisms (natural enemies) to help control populations of invasive weeds.

biological control agent — a natural enemy that has been authorized by the appropriate regulatory agencies to be used within a specific political region.

classical biological control — the use of exotic host-specific natural enemies to help control an invasive species (e.g., a non-native weed). The natural enemies are discovered in the region of origin of the weed, tested for safety, permitted, and intentionally released to establish a self-sustaining population to reduce density of the target weed.

CDFA — California Department of Food and Agriculture

diapause — a state of arrested development usually during seasonal adverse environmental conditions, such as during summer (aestivation) or winter (hibernation). Diapause can occur in the egg, larval, pupal, or adult stage, depending on the insect species.

EA — Environmental Assessment, a document that assesses the risks of a proposed action on the environment or human beings. This document is prepared and made available to the public in compliance with the National Environmental Policy Act (NEPA) of 1970.

FONSI — Finding of No Significant Impact, a document required for a federal agency to comply with the National Environmental Policy Act (NEPA) that concludes that an agent is safe and can be authorized to be released.

natural enemies — herbivores or pathogens that eat or infect an organism (e.g., a target weed).

notho — prefix indicating that a taxon is the result of hybridization.

parasitoid — an insect that parasitizes another kind of insect, which usually kills it.

pupa (pl. pupae) — the developmental stage in which insects transform from larvae to adults.

sp. — species (singular); ssp (plural).

subsp. — subspecies.

SWFL — southwestern willow flycatcher (*Empidonax traillii extimus*), a federally endangered bird subspecies.

TAG — The Technical Advisory Group for Biological Control Agents of Weeds is a committee to provide APHIS scientific review of petitions that evaluate the safety and potential risks of introducing a new biological control agent. It consists of representatives from federal agencies of the USA, Canada and Mexico that have land management responsibilities, the National Plant Board, and the Weed Science Society of America.

taxon (pl. taxa) — a taxonomic group, such as species, genus, or family.

tephritid — this refers to the fruit fly family Tephritidae in the insect Order Diptera (flies).

USDA — United States Department of Agriculture.

USFWS — United States Department of Interior's Fish and Wildlife Service, the agency responsible for protecting federally listed threatened or endangered species.

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https://biocontrol.entomology.cornell.edu/index.php

IOBC Internet Book of Biological Control
http://www.iobc-global.org/publications_iobc_internet_book_of_biological_control.html

Oregon Department of Agriculture Weed Biological Control Program
https://www.oregon.gov/ODA/programs/Weeds/Pages/BiologicalControl.aspx

Pacific Northwest Pest Management Handbooks: Weed Biological Control
https://pnwhandbooks.org/weed/biological-control

Current Status of Biological Weed Control Agents in Oregon, Washington, and Idaho
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USDA-APHIS Technical Advisory Group (TAG) for Biological Control Agents of Weeds
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6.1 *Arundo* (*Arundo donax*)

Lead author: Dr. Patrick J. Moran

Overview

Three insects are permitted for release as biological control agents of *Arundo*, or giant reed, including the shoot tip-galling wasp *Tetramesa romana* (Hymenoptera: Eurytomidae), the rhizome- and shoot-feeding armored scale *Rhizaspidiotus donacis* (Hemiptera: Diaspididae), and the *Arundo* leafminer *(Lasioptera donacis)* (Diptera: Cecidomyiidae).

The *Arundo* wasp is native to Mediterranean Europe (Marshall et al. 2018). This small ($^1/_8$ to $^1/_4$-inch long), black wasp (Fig. 1) is harmless to humans and animals. The female wasp curls its abdomen and lays eggs in the stem near shoot tips with its needle-like ovipositor, which stimulates the formation of galls in which the larvae develop. The wasp can develop only on *Arundo* (Goolsby and Moran 2009, Goolsby et al. 2020). The adults are almost all females, and they can reproduce without mating. Adults live 2 to 5 days and can produce an average of 26 offspring (Moran and Goolsby 2009). Pupation occurs inside the gall and adults chew a small, round 'exit hole' to emerge from the gall (Fig. 1). Looking for and counting exit holes is the easiest way to diagnose the wasp's presence and to determine its abundance. The wasp life cycle takes about 33 days at 80 °F and 50-60 days under variable field conditions between 60-90 °F. Pupae and adults can survive both prolonged drought and winter conditions inside galled shoot tips before emerging. In northern California, the *Arundo* wasp has been released since 2010 at four sites on private land in along Stony Creek in the Sacramento River watershed (Orland, Glenn County), since 2015 at one site in eastern Contra Costa County near Oakley (Big Break Regional Park), at two sites in Sacramento County near Rio Vista and Walnut Grove along the Sacramento River, and, since 2017 at nine sites extending from Orland in the northern sacramento River watershed to Berenda Slough and Cottonwood Creek near Madera (Madera County). Two years after the 2017 releases, reproductive populations of *Arundo* wasps were observed in the summer of 2019 at one site each in Orland, Glenn County, and in Madera, Madera County. It is too early to evaluate the impact of the *Arundo* wasp in California. Seven years after initial release in Texas, it has had moderate impact, reducing live biomass (weight) of *Arundo* shoots 30-40%, leading to a two-to-four-fold increase in the abundance of native plants (Goolsby *et al.* 2016; Moran *et al.* 2017). Adventive (accidentally introduced) populations of the *Arundo* wasp have been found in Santa Barbara, Ventura, Los Angeles, Orange, San Diego, and San Bernardino counties in coastal watersheds (Dudley *et al.* 2008).

The *Arundo* armored scale feeds and reproduces solely on *Arundo* in the field (Goolsby et al. 2009, 2010). Adult females are about $^1/_{16}$-inch in size, and are immobile, with no legs or antennae. They use their stylet-like mouthparts to suck fluids from the vascular tissues of tuber-like arundo rhizomes (roots) and the bases of the shoots. Adults produce tiny (less than $^1/_{32}$-inch long) crawlers, which disperse a few feet at most before settling at a permanent feeding site. Each adult female can produce 85 crawlers on average (Moran and Goolsby 2010). Crawlers secrete a white waxy covering and molt to a second immature stage, which secretes a brown scale covering and continues to develop. Adult males emerge about 6 to 8 weeks after the crawler stage. The short-lived, winged adult males mate with immobile adult females. These females then expand their bodies over 2-fold in size as they continue to feed and

develop crawler embryos. The total life cycle of the female requires five to six months (Moran and Goolsby 2010). The scale is established at release plots at several sites in southern Texas. Combined with the wasp, the scale is having moderate impact in these plots, reducing live shoot biomass by up to 50% compared to plots with the wasp alone (Goolsby and Moran 2019). Initial establishment of the arundo armored scale is typically seen as sparse populations on rhizomes, but over time, dense populations can develop on rhizomes and on the bases of shoots, causing a "witches' broom" distortion symptom.

The armored scale was first released in northern California in 2014-2015 at several sites along Stony Creek near Orland in Glenn County. In 2017-2018, armored scales were released at seven sites: two near Orland, two near Rio Vista and Walnut Grove along the Sacramento River (Sacramento County), and three on Berenda Slough and Cottonwood Creek near Madera (Madera County). In 2019, establishment of sparse populations of reproductive females was confirmed in at least one release plot at all seven sites. Adult females were found on resident *Arundo* rhizomes, and the females produced crawlers in the lab, indicating that many more unsampled adult females are likely producing crawlers at the field sites. In 2018, an adventive population of the *Arundo* armored scale was found in the Santa Clarita River drainage in Ventura County (A Lambert and T. Dudley, UC Santa Barbara, unpubl. data).

Dispersal of the armored scale is far slower than for the wasp, and so long-term impact is likely to be localized to release plots until flooding events or other disturbances distribute the scale throughout watersheds.

The *Arundo* leafminer is a tiny, mosquito-like insect that is host-specific (Goolsby et al 2017) and mines the leaf sheaths of *Arundo*. It is permitted for release in the USA but has not yet been released due to difficulties in rearing adults outside the lab. This insect is not currently available for release in California.

The *Arundo* aphid, *Melanaphis donacis* (Hemiptera: Aphididae), is present in California as an adventive (accidentally introduced) natural enemy. The aphid appears to be widespread, but its actual distribution and impact in California are unknown. It is visible as small ($^1/_{16}$-inch), white, waxy, or powdery adults and smaller immatures (nymphs) mostly on the underside of *Arundo* leaves. Infested leaves and others nearby become sticky with the 'honeydew' excreted by the aphids. This aphid is parasitized by various parasitic wasps, turning the adults into round, brown 'mummies' from which wasps emerge. The *Arundo* aphid is **not** permitted by the California Department of Food and Agriculture for redistribution and use as a biological control organism in California.

Biological control agents of *Arundo*

Species	Common name	Distribution	Impact[1]	Notes
Tetramesa romana	*Arundo* wasp	Limited	unknown	First released in n CA in 2010, adventive in southern California
Rhizaspidiotus donacis	*Arundo* armored scale	Limited	unknown	First released in n CA in 2014, adventive in Ventura County
Lasioptera donacis	*Arundo* leafminer	none in field	N/A	Approved for release in USA. Not yet released.
Melanaphis donacis	*Arundo* aphid	widespread	unknown	Adventive. Not a permitted agent.

[1]Too early to evaluate impact in northern California. Impact demonstrated in Texas.

How the Technique is Employed

Field sites should be surveyed to determine if the *Arundo* wasp and armored scale are present. If the insects are already present, there is no benefit to releasing more.

The *Arundo* wasp can be sampled most easily by standing in one place in the *Arundo* patch for 2 minutes and counting all exit holes visible in a 360-degree turn, then repeat at at least five locations at the site, spaced at least 30 feet apart. Because the wasp makes galls on shoot tips, most exit holes (Fig. 1) will be at head height or higher on side shoots. If you see young main shoots (less than 2 feet tall) in the understory with galls, with or without exit holes, this is clear evidence of establishment of a large arundo wasp population. Galled young main shoots will be bent at an abrupt angle and can thus be distinguished from non-galled main shoots, even if no exit holes are present.

Arundo wasps can be released as piles of shoots with fresh galls (without or with few exit holes) cut from established sites, transported to new sites, and laid on the ground near *Arundo*; or as adults collected from galls in the laboratory and released as adults. To collect adults, strip leaves off galled main shoot pieces (approx. 18 inches long), or axils with live galled side shoots. Avoid collecting side shoots with many exit holes, as they will no longer contain adults. Wax the cut ends of the shoots with paraffin (e.g., Gulf Wax) melted under low heat. This step helps retain moisture in the galls. Place galled shoots vertically into an emergence container such as a Plexiglas cage or large clear plastic or cardboard bin. Use an insect aspirator to collect adults every other day. Check collections for other insects and remove them. *Arundo* wasps can be easily distinguished from other insects by their black bodies, pointed abdomens, and long antennae with 'rings' on the females (Fig. 1). If needed, wasps can be stored in plastic vials for one week in a refrigerator without food. When transporting vials to a field site, allow wasps to warm to room temperature, but protect from sunlight and excessive heat. Release by opening the vial on leaves near arundo shoot tips. The best season for conducting arundo wasp releases is April through July.

The *Arundo* armored scale is most easily sampled by scraping back a little gravel or dirt from the base of buds on rhizomes that are six months to one year old (Fig. 2). These rhizomes can be found near the edge of *Arundo* patches underneath live, mature (with inflorescence tufts) shoots. Peel back the dead, pointy leaf-like structures attached to the rhizomes and look for adult female scales on the rhizome or look on shoot buds or the bases of shoots. If scales are seen, rhizome samples can be cut with a powered reciprocating saw or hand saw and levered out of the ground with a shovel for further examination. A light microscope at 10X power is required to count the females, and the much smaller male scales can usually be seen as brownish spots attached to the female scales. *Arundo* patches with well-established wasp and armored scale populations will lack vigor (see banner image). One-half or more of the main stems will be dead or dying. Live main shoots with dead/broken-off side shoots will be common. Female *Arundo* scales may be present on side shoots as well as on rhizomes, and tiny males will be present on leaf collars. It will be possible to easily see through the stand, as opposed to the impenetrable 'wall' formed by vigorous *Arundo*. Other factors such as drought can decrease vigor as well; however, so it is always best to sample for insects to confirm their presence.

The *Arundo* armored scale can be released most easily by digging up pieces of infested rhizome (about the size of a baseball), cutting off roots on the underside, transporting them to the new site and

positioning them on the edge of *Arundo* patches. Scrape back the soil to expose pink or light brown buds and the tops of rhizomes, then position the infested rhizome pieces near the exposed resident rhizomes. Mark release locations with flagging tape or pin flags. Cover rhizome pieces and exposed recipient buds and rhizomes with a light layer of mulch (i.e., dead *Arundo* leaf material) to provide some protection against heat and desiccation of the scales. The best time to conduct armored scale releases is late fall through winter (November through March).

Special Tips

The *Arundo* wasp performs best when there are abundant young side shoots less than 4 inches in length and a few to abundant young main shoots (no more than 2 feet tall), as each shoot provides a tip on which the wasp can deposit eggs. To enhance production of shoot tips prior to wasp release, "top" (cut) plots (e.g., 7x7-foot) with hand loppers or a power tool to 5 feet (roughly chest height) or to ground level (Fig. 3). Cutting should be done in spring in soil that is at least somewhat moist (e.g, March in southern CA, April in northern CA). Remove debris from the plot to allow room and sun for new shoot growth. If cutting must be done in the summer or fall, watering of the plots after cutting is recommended to encourage regrowth. Mark plot locations with flagging tape or pin flags. The "topping" technique produces more vigorous, bushy, dense regrowth of side shoots than does ground-cutting, which leads to production of new main shoots. A "double-cut" technique, in which plots are first cut to ground level in early spring and then "topped" 2 to 3 months later, may produce an optimal mix of main and lateral shoots. Release *Arundo* wasps as either galled shoots or adults, beginning four weeks after final cutting. Releases may continue for 1 to 2 months following initial release. If no pre-cutting is done, release galls/wasps in the spring to early summer in stands of arundo with 5 to 15-feet-tall main shoots that are producing abundant new side shoots. Check the plots for establishment every 2 months (except in winter) using the 2-minute count technique.

The *Arundo* armored scale will also benefit from "topping" or ground-cutting arundo prior to its release, as this pre-treatment will induce production of new shoot buds. Releases should be conducted in the fall-winter time frame noted above, six months after spring cutting. If no pre-cutting is done, conduct releases near the edges of *Arundo* stands, where there are young buds suitable for colonization. Collect a small sample of rhizome (e.g., 6x6-foot square) from each release point annually, beginning one year after release and examine as noted above. Beginning two years after release, establishment can also be checked more rapidly by counting the number of leaf collars within 3 to 4 feet of the release point that have male scales and expanding outward each year if males are seen.

Biological control of *Arundo* can be complementary to herbicide treatments or mechanical control, especially if there are areas that escape the treatment (too difficult to access or too environmentally sensitive). Leave plots of the *Arundo* untreated (at least 7x7-foot square) for biological control releases.

Caveats

No Federal or state permits are required to move the *Arundo* biological control agents within California, but various landowners/agencies may have their own permitting requirements for releases on their lands.

Do not treat *Arundo* chemically, mechanically, or with fire at locations at which the biocontrol agents have recently (within the past year) been released. When releasing the *Arundo* wasp and scale, avoid sites/plots subject to winter flooding. However, once they are well established, both insects will likely persist after flooding. Check sites for signs of the wasp and scale after floodwaters recede.

Insecticide drift from applications to crops can limit *Arundo* wasp establishment, and many *Arundo*-invaded waterways are adjacent to crops.

Where Can I Get These?

There are currently no commercial sources for the *Arundo* wasp or scale in California. A landowner that has existing populations may be willing to act as a 'donor' for *Arundo* wasp and armored scale populations. There are currently only two known sites (one in Glenn County and one in Madera County) with established populations of both agents in northern/central California. Contact the USDA-ARS author listed above. Wasp availability varies greatly by season, with late winter through early summer being the best time to collect galled shoots.

Photographs

Figure 1. Left: Adult *Arundo* wasp (*Tetramesa romana*) under 40X microscope. Right: Exit holes on shoot tip. Photo credit: USDA-ARS.

Figure 2. Left: Adult female *Arundo* armored scale (*Rhizaspidiotus donacis*) dissected from its waxy scale covering under 50x microscope. Center: Dense colony of armored scales (arrows) on *an Arundo* rhizome. Right: Demonstration of where to look (arrow) for low-density colonies of armored scale in the field after peeling back dead leafy outer rhizome layer. Photo credit: USDA-ARS.

Figure 3. *Arundo* topping or ground cutting as a technique to enhance *Arundo* wasp and armored scale establishment. Left: *Arundo* plot immediately after topping with debris removed. Center: Regrowth after 4 weeks (May to June) in a topped plot, showing abundant side shoot regrowth. Right: Regrowth after four weeks during the same time of year after ground-cutting of an *Arundo* plot showing abundant main shoot regrowth. Photo credit: USDA-ARS.

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6.2 Bull Thistle (*Cirsium vulgare*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Bull thistle has one approved biological control agent in California: the gall fly, *Urophora stylata* (Diptera: Tephritidae). Adult female flies deposit their eggs in young flower buds. Larvae burrow into the flower head and induce the formation of a hard, woody gall which reduces seed production. Adult flies emerge in late May and June, mate, and females visit flower heads and deposit eggs in July and August. Many larvae can develop inside one head (Fig. 1). When the larvae have finished their development, they hibernate in the head during winter and early spring (Fig. 2). This fly has one generation per year. On a population level, this gall fly has been estimated to reduce seed production by 60%. Adults are about the size of house flies. The body is light gray, and the wings are clear with a dark "IV" marking.

In California, *U. stylata* was released at 24 locations statewide, but it formed permanent populations at only three locations: San Simeon, San Luis Obispo County; Tomales, Marin County, and Eureka, Humboldt County (Fig. 3). All three locations are within 10 miles of the coastline (see Fig. 1). While the fly is able to build up high populations (over 50% of heads attacked) where it established, its limited distribution severely reduces the benefits this beneficial organism can provide statewide. *Urophora stylata* has not been found attacking any other plant species.

Biological control agents of bull thistle

Species	Common name	Distribution	Impact	Notes
Urophora stylata	gall fly	limited	moderate	First released in CA in 1993

How the Technique is Employed

Look for signs of the gall fly by examining old flower heads. Using a leather glove, un-infested heads will give or collapse when squeezed with fingers, infested heads with galls are hard and resist being squeezed. Adult flies can be found on open flower heads in June through August. The bull thistle gall fly may be particularly useful in areas where populations of bull thistle persist from year to year. Many bull thistle populations are transitory, colonizing recently disturbed sites then slowly die out as more permanent vegetation establishes.

Adult flies can be collected in the field by sweep net. Alternatively, galled seedheads can be collected in the fall and winter and placed in large-mesh fruit bags, such as orange bags, at field sites where adult flies will emerge in the spring. The bags protect the heads from being eaten by rodents and the large mesh allows the adult flies to escape.

The gall fly should be released where bull thistle populations are large and immediate eradication is not the primary objective.

Special Tips

The bull thistle gall fly is present in plants throughout the year. Adult gall flies emerge in June and are active visiting flower heads in July and August while larvae are present inside seedheads during the other ten months. Dead seedheads laying on the ground may contain live gall fly larvae, so it is best not to remove them until adults have finished emergence in the spring.

Caveats

Herbicides that kill bull thistle rosettes during the winter or early spring, before adult flies emerge, may reduce plant populations and not affect adult emergence.

Where Can I Get These?

The gall fly is available on a very limited basis because of its restricted geographic distribution and because the transitory nature of bull thistle populations prevents establishment of field nursery sites.

Insects may be available from your county Agricultural Commissioner or the CDFA Biological Control Program located in Sacramento.

There are no known commercial vendors of this beneficial insect.

Photographs

Figure 1. Left: Bull thistle gall fly (*Urophora stylata*) adult male. Photo credit: Peter Harris, Agriculture and Agri-Food Canada, Bugwood.org. Right: Female with extended ovipositor. Photo credit: Martin Hauser, CDFA.

Figure 2. Bull thistle gall fly galls and larvae in flower head. Photo credit: Peter Harris, Agriculture and Agri-Food Canada, bugwood.org.

Figure 3. Bull thistle gall fly release locations (plant location data from CalWeedMapper). Blue ring = failed to establish; yellow ring = established; red dot = bull thistle in Calflora, blue dot = Consortium of CA Herbaria.

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6.3 Canada Thistle (*Cirsium arvense*)

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Overview:

Canada thistle has three approved biological control agents in California: the stem gall fly, *Urophora cardui* (Diptera: Tephritidae), the stem weevil *Hadroplontus litura* (formerly called *Ceutorhynchus litura*; Coleoptera: Curculionidae), and the rust pathogen *Puccinia punctiformis* (Pucciniales: Pucciniaceae). The stem weevil holds the most promise of the permitted insects.

The stem gall fly was first released in 1977 and now occurs in several counties in northern California (Fig. 1). However, it rarely attacks more than a handful of plants where found. Females lay eggs in young stems which stimulate the formation of a gall. Multiple larvae develop inside each gall and hibernate inside the gall. Adults emerge in late spring. Adults have clear wings with a thick black "W" marking. Semi-shaded sites are slightly preferred to those in full sun.

The stem weevil was first released in 1971 but it failed to establish (Fig. 2). New release efforts that began in 2012 have resulted in a population of the stem weevil that persists at one location near Etna in Siskiyou County. Adults emerging in late winter feed on the young leaves of plants and females deposit eggs in the young leaves in the late winter and early spring. The larvae mine down the leaf midrib into the root crown and lower stem (Fig. 2). Mature larvae exit the plant and pupate in the soil. The exit holes allow access for small insects and pathogens which can further damage the plant. The underground parts of the plant usually do not survive the winter, and it has been suggested that *H. litura* may reduce overwintering survival of Canada thistle plants. Adults are black with a white 'T' or thunderbird-shaped marking on their back.

The Canada thistle rust is found occasionally on plants in Siskiyou and Lassen counties. It infects the leaves and stems but appears to have little impact on plant survivorship or seed production (Fig. 3). However, there is a study currently underway to artificially inoculate plants with the rust in the fall when the plants are translocating nutrients down to the root system. If the rust infects the root, the disease will be translocated throughout the clonal root system and the thistle patch will die out. Results of this control method are still pending and will not be available until after 2021.

Currently, the most common insects on Canada thistle in California are two accidentally introduced species, **the seed head weevil**, *Larinus carlinae* (formely called *L. planus*; Coleoptera: Curculionidae; Fig. 4), and **the seed head fly**, *Terellia ruficauda* (Diptera: Tephritidae; Fig. 5). Larvae of both species feed on the developing seeds and reduce seed production. *Larinus carlinae*, the more common insect, completely destroys all seed when its larva is present in a head. It can become locally abundant, and, at high population levels, it can destroy over 90% of seed produced in a patch of plants. The seed head fly is less common (attack rates usually less than 20%) and does not provide population-level impacts.

Another seed head weevil (*Rhinocyllus conicus*), which was released in California and other states primarily to control musk and Italian thistles, attacks Canada thistle at low levels. Generally, 2-12% of the early seed heads can be found with *R. conicus* eggs. However, few *R. conicus* larvae mature to adults because feeding by adult L. carlinae kill young buds and results in high mortality of young *R. conicus*

larvae that are present in the heads. However, extensive sampling by CDFA scientists indicates that it rarely occurs on Canada thistle in California.

Biological control agents of Canada thistle

Species	Common name	Distribution	Impact	Notes
Hadroplontus litura [= *Ceutorhynchus litura*]	stem weevil	Limited	unknown	First released in CA in 1971, re-released in 2011
Larinus carlinae [=*L. planus*]	seed head weevil	widespread in northern CA	moderate	Accidental introduction, found in CA in 2014. Not a permitted agent.
Puccinia punctiformis	Canada thistle rust	Limited	unknown	Present but not intentionally released – experimental use permit for CA in 2019
Rhinocyllus conicus	Seed head weevil	Widespread	Low	Released as an agent on musk thistle. Not a permitted agent.
Terellia ruficauda	seed head fly	Widespread in Siskiyou, Lassen, Modoc cos.	Low	Accidental introduction, found in CA in 1942. Not a permitted agent.
Urophora cardui	gall fly	recovered in Siskiyou and Lassen cos.	Low	First released in CA in 1977

How the Technique is Employed

The stem gall fly has too little impact in California to be recommended for use as a control organism. Collect galls in the fall, winter or early spring and place them at new sites. It would be best to rear out adults indoors in a cage to prevent the unintentional movement of parastoids.

Of the permitted insects, the stem weevil holds the most promise. Adults should be collected in early spring to release when stems are short (less than 2 inches tall). Use fingers, forceps, or aspirator.

The fall inoculation of the Canada thistle rust has shown good results in Colorado where summer rains are common. Whether it will work in California is under study.

The two seed head insects likely occur at most infestations of Canada thistle in Siskiyou and Lassen counties. Look for signs of the seed head weevil by examining old flower heads for the presence of a small white larva when opened. These insects invaded California on their own and are not permitted for release. The weevil is known to attack at least 4 species of native thistles (*Cirsium* spp.) in other western states, but in California it has been found only on Canada thistle to date.

Special Tips

Dead plants with seed heads laying on the ground at the end of the season may contain live insect larvae, so it is best not to remove them until adults have finished emergence in the spring.

Caveats

The stem weevil, stem gall fly, rust, and the adventive seed head fly attack only Canada thistle and have not been found on native thistles.

The seed head weevil has been reported to attack four nontarget native thistles (*Cirsium* spp.) in the western USA. However, in a recent survey in California, it was found only on Canada thistle and not on any native thistle species.

Where Can I Get These?

The use of the rust as a control agent is currently under study and not available for general distribution.

Commercial vendor of the Canada thistle stem weevil:
Integrated Weed Control (1-888-319-1632) website: www.integratedweedcontrol.com

Photographs

Figure 1. Left: Canada thistle gall fly (*Urophora cardui*) adult. Photo credit: Laura Parsons, University of Idaho, PSES, Bugwood.org. Right: Stem gall. Photo credit: Baldo Villegas, CDFA.

Figure 2. Left: Canada thistle stem weevil (*Hadroplontus litura*) adult. Photo credit: Baldo Villegas, CDFA. Center: Adult feeding damage. Photo credit: Baldo Villegas, CDFA. Right: Larvae feeding inside stem. Photo credit: Norman E. Rees, USDA Agricultural Research Service – Retired, Bugwood.org.

Figure 3. Canada thistle rust (*Puccinia punctiformis*). Photo credit: Joel Price, Oregon Department of Agriculture, Bugwood.org.

Figure 4. Canada thistle seed head weevil (*Larinus carlinae*). Photo credit: Baldo Villegas, CDFA.

Figure 5. Canada thistle seed head fly (*Terellia ruficauda*). Photo credit: Martin Hauser, CDFA

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6.4 Cape-Ivy (*Delairea odorata*)

Lead authors: Dr. Patrick J. Moran, Dr. Scott L. Portman

Overview

One biological control agent of Cape-ivy is permitted for release in California, the shoot tip-galling fly *Parafreutreta regalis* (Diptera: Tephritidae), which is native to South Africa. The Cape-ivy fly was discovered by USDA-Agricultural Research Service (ARS) scientists working with South African scientists in the early 2000s. After testing over 99 plant species in a quarantine laboratory to verify that the fly can make galls only on Cape-ivy (Balciunas et al. 2010) and demonstrating that the galls can reduce plant size by 30 to 50% in greenhouse tests (Balciunas and Smith 2006) a permit for field release was obtained in 2016 from USDA-APHIS and CDFA. The Cape-ivy fly is the first biological control agent in the world targeting Cape-ivy.

The Cape-ivy fly adults are about $^1/_8$ to $^1/_4$-inch (Fig. 1), live up to 4 weeks, and females can lay up to 100 eggs (Balciunas and Smith 2010). Eggs are laid in the plant stem near a growing tip and stimulate the formation of a gall. Larvae feed on the gall tissue as it forms, and the galls increase in size to about that of an olive ($^3/_4$ to 1 inch long). However, gall size is variable and depends on the size and number of larvae inside the gall and the plant's vigor/health. Larvae go through three growth stages (instars) and chew an 'exit window' in the gall prior to pupating. Adults emerge after about two weeks and break through the 'window' to emerge from the gall. The Cape-ivy fly can complete one generation in about 2 months in a greenhouse at 75°F. There are several generations per year, with a slowdown of activity during the winter months.

The Cape-ivy fly was released between 2016 and 2019 at 18 sites between Humboldt and Santa Barbara counties on both public and private lands (Moran and Portman 2020). Releases were initially conducted once in the fall or spring, but this technique had a low level of successful establishment. In 2018-2019 a new technique was used of performing five releases, at monthly intervals, at each site, using a release cage that confined adult flies for 3 to 4 weeks, then moving the cage and releasing new adults into the cage. This method led to establishment of the fly at four sites to date, including one just north of Santa Cruz (Santa Cruz County), two sites in Big Sur (Monterey County), and one site in San Luis Obispo (San Luis Obispo County) along streams and in coastal scrub (Portman and Moran 2020). Fly populations are increasing rapidly, with some locations having gall densities of over 10 galls per square yard. Additional Cape-ivy fly field release sites in Santa Barbara and Los Angeles Counties are being evaluated for population establishment by university scientists. In 2019-2020, a new release technique, involving the planting of greenhouse-galled plants at field sites (Fig. 6), was tested, with initial evidence of establishment at one site in Sonoma County and one site in San Mateo County. The impact on the fly on Cape-ivy is unknown, but studies are underway to determine its effects.

The leaf- and stem-mining moth, *Digitivalva delaireae* (Lepidoptera: Glyphipterigidae), which, like the fly, originates from South Africa, is being evaluated as a candidate biological control agent in the ARS laboratory in Albany, CA. It appears to have a narrow host range (Mehelis et al. 2015) but can make

mines on two native *Senecio* species in the lab. Additional testing is underway to determine if the moth is sufficiently safe to use.

Biological control agents of Cape-ivy

Species	Common name	Distribution	Impact[1]	Notes
Parafreutreta regalis	Cape-ivy shoot tip-galling fly	limited	N/A	First released in 2016 in CA.

[1]Too early to evaluate impact in the field.

How the Technique is Employed

The Cape-ivy fly is not currently available for re-distribution, as populations from the first field releases are still establishing and cannot be disturbed. It is anticipated, however, that re-distribution will become possible within the next few years. No Federal or state permit is required to move the Cape-ivy fly within California, but various private landowners and public agencies may have their own permitting requirements for releases on their lands.

Each field site should first be surveyed to determine if the Cape-ivy fly is already present, especially if the site is located between San Francisco and San Luis Obispo. Make a small (1 ft^2) sampling square of PVC and throw it randomly into the Cape-ivy. Examine shoots for galls (see Fig. 1) and consider counting number of galls with and without either intact exit "windows" (indicative of pupation) or exit holes (indicative of adult emergence). Count the number of galls and total number of shoot tips (galled and ungalled). Collect data for at least 10 sampling square 'throws' per site. If the Cape-ivy fly is already present at the site, survey again in 3 months and look for signs of dispersal and/or galled shoot population density increase. If population increases are occurring, there is no benefit to releasing more flies.

To distribute the fly, collect mature galls (about 50) at established field sites with about an inch of stem below the gall. To keep galls fresh so that adults will emerge, stick the stem into moist florist's foam and place them upright in a ventilated cardboard or plastic container. The container should be protected from extreme heat/cold and kept indoors. Adults can be collected from the containers using a hand-held insect aspirator. Adults can be held in a refrigerator for up to one week if not convenient for immediate release. To maximize the chance of release success, it is best to determine the number of female and male flies; this can be done easily be examining the tip of the fly abdomen from either the side or underside while flies are in vials (for easy counting limit flies per vial to 10). Females have a thick black structure (V-shaped when seen from below) at the end of the abdomen known as the ovipositor, while males lack this structure (Fig. 2).

Vials containing adult flies (at least 20, even ratio of females:males) can be released onto healthy Cape-ivy shoots in the field. If possible, construct a cage made of PVC frame (2x2-foot square sides and 15-inch height) and cover with a breathable fabric such as muslin (see Fig. 1). Stake down the edges of the cages with dog or tent stakes, being careful not to crush Cape-ivy stems, and reach underneath the cage to release the flies or detached galls inside the cage before completing the stake down process. Alternatively, adults or galls may be released without cages, but this approach makes it more difficult to

track initial release success. The USDA-ARS has recently obtained preliminary evidence of the establishment success of a release method using potted galled plants, generated in a greenhouse colony, as sources of flies for field releases. Galled plants are being planted in a circle for about three months to let the adult flies emerge over time and colonize resident Cape-ivy plants. To release using this technique, it is necessary to first propagate Cape-ivy in a greenhouse and expose plants after about 6 weeks of growth to flies in greenhouse cages.

If releasing flies in field cages, remove the cage after 4 weeks. If more flies are available, move the cage to a new location at least 150 feet away and repeat the release procedure. Mark each cage location with pin flags. If no cage is used, mark the point of release. Two months after a release, count galls in the former cage location, or in a circular plot about 10 feet in diameter around the point of uncaged release. Make separate counts of galls with and without 'windows' (Fig. 1), opaque round spots which are chewed by larvae before they pupate. There may also be galls with open 'windows' (round holes), indicating that adult flies have emerged. By 6 months after the original release, if the release was successful, 'second generation' galls outside of the formerly-caged location(s) will be observed. Use the PVC square technique above to survey for galls outside the release location(s) along a random walk or on at least two linear transects in opposite directions from the release location. Check for overwintering and establishment the following spring using the same methods. If establishment occurs at the release patch, survey other non-connected Cape-ivy invasions at your site beginning the second year after release.

Establishment is expected to reduce live Cape-ivy shoot tip density, percent cover, and spread into new habitats, but the USDA-ARS is still evaluating the impact of the fly. If flies disperse to your site or releases lead to establishment, perform annual monitoring of Cape-ivy stem tip density, percent cover, and abundance and diversity of other plant species.

Special Tips

Releases are best performed in the spring or summer (March to August).

If Cape-ivy occurs in more than one habitat type (e.g., shady riparian and open scrub/bluff), release in each habitat type and compare success of establishment.

Biological control of Cape-ivy can be complementary to herbicide treatments or mechanical control, but only if there are areas that escape the treatment (too difficult to access or too environmentally sensitive). Do not treat areas/plots at which the biocontrol agents have recently (within the past year) been released or have dispersed naturally, or at the very least, set aside 'refugia' plots at least 10x10-foot square for the biocontrol agents to develop their populations.

Caveats

Do not release on wilted (drought-stressed) Cape-ivy, as it is inferior as a host for the fly. Do not release in fall or winter. Fall releases may involve drought-stressed plants, and releases in winter will expose the fly to low temperatures (frost can kill the shoot tips) and wet conditions that suppress adult activity and slow gall development.

Do not release along trails or other areas subject to trampling/disturbance.

The ability of Cape-ivy fly populations to survive flooding is not known. However, galls can be made on both ground-covering Cape-ivy and on stems hanging from shrubs and trees, so some of the galls are likely to survive.

Where Can I Get These?

There are no currently commercial sources for the Cape-ivy fly. The fly is not widely established but is expected to become well-established over the next few years. Contact the USDA-ARS authors for more information.

Photographs

Figure 1. Left: Cape-ivy shoot tip-galling fly (*Parafreutreta regalis*) adult on a Cape-ivy leaf magnified about 5x. Center: Cape-ivy galls in the field showing different gall shapes and sizes. Gall on the left has an exit 'window' made by larvae prior to pupation. Right: Cape-ivy fly release cage. Photo credit: USDA-ARS.

Figure 2. Left: Lateral view of Cape-ivy shoot-tip galling fly (*Parafreutreta regalis*) adult female under microscope, showing black ovipositor at tip of abdomen. Right: Lateral view of adult male fly lacking the black ovipositor. Photo credits: USDA-ARS.

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6.5 Dalmatian Toadflax (*Linaria dalmatica*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

There are 5 species of permited and 3 accidentally introduced insects that attack yellow toadflax (*Linaria vulgaris*) and/or Dalmatian toadflax (*L. dalmatica*) in the USA, but only one of these is permitted in California.

The stem weevil was initially believed to be one species of weevil ("*Mecinus janthinus*") that attacks the stems of both yellow and Dalmatian toadflax. However, molecular genetic analysis has clearly shown that there are two species of weevil: *Mecinus janthiniformis* (Coleoptera: Curculionidae) prefers Dalmatian toadflax, and *M. janthinus* prefers yellow toadflax. Both species were released in Canada and east of the Rocky Mountains (first in Montana in 1996). On its own, *M. janthiniformis* has spread into northeastern California (Modoc, Siskiyou, Lassen, and Shasta counties). CDFA issued a permit to intentionally release *M. janthiniformis* into areas south of 34.82° N latitude (the northern border of Kern County) because of concern that this weevil can attack a native snapdragon, *Antirrhinum virga*, which occurs in the Coastal Mountains in Lake, Napa, and Colusa counties.

Adult *M. janthiniformis* are good fliers and have been observed to disperse 2 miles in 4 years. There is one generation per year. Adults overwinter inside the plant stems, emerge in spring, feed on leaves, and lay eggs in the stems. Larvae tunnel inside the stems and pupate inside the stems. This agent has been extremely effective in reducing Dalmatian toadflax populations by over 90% at a large infestation at Hungry Valley State Vehicular Recreation Area near Gorman, Los Angeles County, in about 4 years after release. In contrast, most populations of Dalmatian toadflax in northern California are relatively small (less than 5 acres) so the impact of the stem weevil at these locations has not been as dramatic.

The seed weevil, *Rhinusa neta* (Coleoptera: Curculionidae), is an accidental introduction on yellow and Dalmatian toadflax. It is a strong flier and spread on its own into California. It was first recovered in 2017 and occurs on almost all known infestations of Dalmatian toadflax in northern California. The adult female deposits eggs on the seed capsule, and the larvae consume the developing seeds. It has one generation per year. Field observations show that *R. neta* destroyed over 70% of seed in one toadflax population in Trinity County.

Biological control agents of Dalmatian toadflax

Species	Common name	Distribution	Impact	Notes
Mecinus janthiniformis	stem weevil	wide	high	First release in southern CA in 2008; not intentionally released in northern CA where it was first recovered in 2009 - Not a permitted agent north of Kern County
Rhinusa neta	seed weevil	wide	high	Not intentionally released, first recovered in CA in 2017 - Not a permitted agent

How the Technique is Employed

Check to see if the stem weevil is present at your site. Look for signs of insect damage to the stems (holes for laying eggs, tunneling in the pith) or adult feeding holes on the leaves. Adult exit holes should be apparent on old, prior year stems. If the weevil is present, then it is not worth releasing more.

Overwintering adults can be collected by cutting stems that were infested the previous summer (presence of egg holes). These can be held in a refrigerator until ready to release. Release adults when the plants begin to grow in the spring. Alternatively, active adults can be collected in the spring, when plants are bolting, using a sweep net or by knocking them into a container. Provide leaves for the adults to eat and hide in. Keep them cool and release them at the new site as soon as possible.

Detailed information and photographs can be found in (Sing *et al*. 2016).

Special Tips

This biological control agent will multiply if it has a suitable habitat, and the old stems are undisturbed to allow adults to survive until spring emergence.

Caveats

There are no biological control agents permitted for control of Dalmatian toadflax north of Kern County. Both weevils are widespread and provide heavy feeding damage to their host plant. The seed weevil, *R. neta*, has been found in seed capsules of a native snapdragon, *Antirrhinum virga*, in Colusa County.

Killing plants in the middle of the growing season is likely to kill the next generation of weevils, so it is important to leave some areas untreated.

Mowing or burning would have the same effect of decimating the weevil population; however, cutting flower panicles to prevent seed set would not affect the stem weevil.

Herbicides that kill toadflax before it bolts will deprive the insects of a host plant but will give them time to search for the remaining plants that have not been killed. Thus, biological control can be complementary to herbicide or other control treatments, especially if there are areas that are not treated (e.g., too difficult to access or too environmentally sensitive to treat).

Where Can I Get These?

There are no biological control agents currently permitted for use on Dalmatian toadflax north of Kern County. Contact the CDFA Biological Control Program about release information for toadflax populations from Kern County south.

Photographs

Figure 1. Adult stem weevils (*Mecinus janthiniformis*) remain in stems waiting to emerge the following spring. Photo credit: Lincoln Smith, USDA-ARS.

Figure 2. Adult seed weevil (*Rhinusa neta*). Photo credit: Chris Joll.

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6.6 Gorse (*Ulex europaeus*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Gorse has three approved biological control agents in California: the pod weevil, *Exapion ulicis* (Coleoptera: Brentidae), the gorse spider mite, *Tetranychus lintearius* (Acari: Tetranychidae), and the gorse thrips, *Sericothrips staphylinus* (Thysanoptera: Thripidae).

The pod weevil is widespread in California and occurs wherever gorse is found (Fig. 1). The adult female emerges from overwintering in early spring when gorse is in flower and feeds on the yellow flower petals and pollen. Later, when the pods form and the seeds begin to swell, the female chews a hole in the pod and lays a clutch of eggs. The larvae burrow into the developing seeds and consume them from inside. The larvae develop to adults inside the pod. Adults leave when the mature pod dries and splits open, and they hide in sheltered places such as soil litter during the summer and winter. About 60% of pods are infested with weevils, resulting in destruction of 30-40% of viable seed.

The gorse spider mite is the first spider mite approved for use as a biological control organism in the United States (Fig. 2). Host specificity of the mite was thoroughly examined, and it was found to be safe. Both immatures and adults feed on the leaf tissue, and the stress from heavy damage can reduce flowering and seed production. Soon after release, the spider mite built up high populations, and whole blocks of plants were covered with their webbing (hence their name “spider” mite). Later, predaceous mites and small ladybugs that specialize on mite predation moved into these areas, and their feeding caused severe declines in the abundance of the gorse spider mites. Currently, the mite occurs at low levels primarily around its original release sites in Marin, Sonoma, Mendocino, and Humboldt counties. Usually, spider mite populations are too low to provide much damage.

The gorse thrips was approved in 2019 as the third biological control agent for gorse in the United States (Fig. 3). Host specificity testing showed this insect to be highly specific to gorse and safe for introduction. Its native range is western Europe and overlaps the native range of gorse in Europe. It has been introduced as a biological control agent in New Zealand, Australia, and Hawaii. Adult females deposit their eggs in slits in young gorse stems, and nymphs and adults feed on leaf and stem tissues. In California, we expect 2-3 generations per year. This is a new agent and its first release occurred on June 5, 2020, in Marin County.

The leaf moth, *Agonopterix nervosa* (Lepidoptera: Depressariidae), is an accidental introduction that commonly occurs on gorse plants (Fig. 4). Its larvae tie leaves together with silk, and in some localities, high populations can cause severe damage to the growing tips. The leaf moth is not permitted for use in California.

Biological control agents of gorse

Species	Common name	Distribution	Impact	Notes
Agonopterix nervosa	leaf moth	wide	low	Accidental introduction, first recovered in the 1920s. Not a permitted agent.
Exapion ulicis	gorse pod weevil	wide	moderate	First released in CA in 1964
Sericothrips staphylinus	gorse thrips	new agent	unknown	First released in CA in 2020
Tetranychus lintearius	gorse spider mite	limited	low	First released in CA in 1994

How the Technique is Employed

The gorse pod weevil is widespread and probably occurs wherever gorse grows in California.

The first release of the gorse thrips occurred in 2020 at a field research site in Marin County. A culture of the thrips is being maintained at the USDA-ARS Invasive Species and Pollinator Health Research Facility, and additional releases in Marin, Sonoma, and Mendocino counties will occur for the next few years.

The spider mite is not recommended because it is usually subdued by predatory mites. See additional information in Andreas et al. (2017).

Special Tips

The pod weevil does best in open, sunny sites, and poorly at sites exposed to saltwater spray.

Caveats

The pod weevil is present on plants from March through July. Adult weevils emerge from split pods in July and are off the plant until flowering in the spring.

The gorse thrips is present on plants all year round. Herbicides that kill plants will be likely to prevent establishment or persistence of this biological control agent.

Where Can I Get These?

The pod weevil is widespread and likely occurs wherever gorse grows in California. There are no commercial sources for this insect. Adults can be knocked off plants in spring by beating branches with a stick or racket so that they fall into an open sheet or sweep net. This is most effective at cold temperatures (e.g., early morning), when insects are less able to fly. Adults can also be reared from mature pods that are collected in late spring (June) before they split open. Place the pods in a container with a fine screen top and wait for the adults to emerge.

The gorse thrips is a part of a new release program by the USDA-ARS and is not yet available. Releases in 2020 are planned for research sites. Once populations establish and build up to high levels, collections for redistribution will become available. There are no known commercial vendors of this beneficial insect.

Photographs

Figure 1. Left: Pod weevil (*Exapion ulicis*) adults on flower. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org. Right: Pod weevil larvae inside seed pod. Photo credit: George Markin, USDA Forest Service, Bugwood.org.

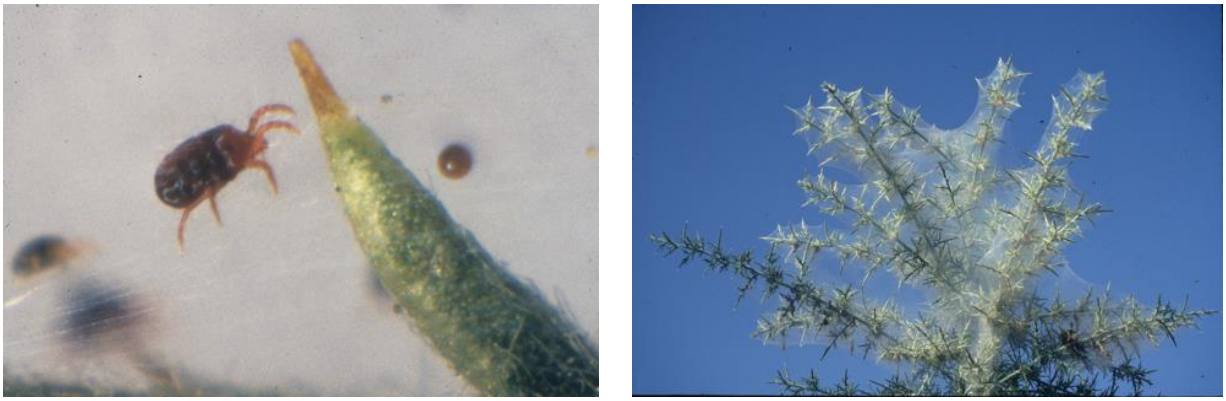

Figure 2. Gorse spider mite (*Tetranychus lintearius*) adult and egg (under a microscope) and webbing. Photo credit: USDA-ARS.

Figure 3. Gorse thrips (*Sericothrips staphylinus*) adults and damage on leaves. Photo credit: George Markin, USDA Forest Service, Bugwood.org.

Figure 4. Leaf moth (*Agonopterix nervosa*) larva. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

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6.7 Knapweeds (*Centaurea diffusa, C. jacea, C. stoebe, C. virgata*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Diffuse (*Centaurea diffusa*), meadow (*C. jacea* nothosubsp. *pratensis*), spotted (*C. stoebe*) and squarrose (*C. virgata* subsp. *squarrosa*) knapweeds are susceptible, to varying degrees, to a suite of biological control agents. These plant species are closely related and some of them hybridize. Thirteen species of insects that attack these plants have been approved for release in the USA, but only 9 are approved for use in California (see table below). These insects may differ in their host plant preference and do not attack all of these plant species equally well. Knapweed agents have been most extensively released in Colorado, Montana, and Oregon, where these knapweeds are most invasive. The status of agents in California are reported below. No damage to non-target species has been reported.

Diffuse knapweed. Diffuse knapweed occurs primarily in Trinity and Siskiyou counties. The two seed head weevils, *Bangasternus fausti* and *Larinus minutus* are well established in California and attack up to 85% of flower heads. The gall fly *Urophora affinis* appears to have gradually disappeared after establishment of the two seed head weevils. Knapweed densities decreased to about one third over an 8-year period after introduction of seed head weevils. The root beetle, *Sphenoptera jugoslavica*, was released and occurs at low levels. The density of diffuse knapweed seed heads per square meter decreased gradually from 1998 to 2008 at a release site. The rust fungus *Puccinia jaceae* var. *diffusa* (not listed in table below) is an unpermitted natural enemy of diffuse knapweed that arrived on its own, but it infects up to 60% of plants in California.

Meadow knapweed. The seed head weevils, *Larinus minutus* and *L. obtusus*, were released in Siskiyou County in 2001, and two years later attacked 74 to 78% of flower heads. The flower heads of meadow knapweed are larger than those produced by spotted and diffuse knapweed, and not all seeds are destroyed by the seed head weevils. The seed head fly, *Urophora quadrifasciata*, dispersed to this plant by itself and attacked 4 to 38% of flower heads.

Spotted knapweed. Two seed head flies (*Urophora quadrifasciata* and *U. affinis*), the clearwing fly (*Terellia virens*), and the seed head weevils (*Larinus minutus* and *Eustenopus villosus*) are established on spotted knapweed in Shasta County. During a 3-year study, *L. minutus* attacked an average of 43% of flower heads, *U. affinis* 40%, and *U. quadrifasciata* 34%. The hairy weevil (*Eustenopus villosus*) released on yellow starthistle was found to attack 9% of the flower heads. *Terellia virens* attacked less than 3% of flower heads. The density of spotted knapweed stems decreased by 78% over 5 years. Attack by *E. villosus* is likely a temporary 'spillover' effect due to insects coming from nearby yellow starthistle populations that declined and deprived the weevils of their preferred host plant. The root weevil (*Cyphocleonus achates*) persists at low levels.

Squarrose knapweed. Two seed head weevils, *Bangasternus fausti* and *Larinus minutus*, and the root beetle, *Sphenoptera jugoslavica*, have been introduced and successfully established over most of squarrose knapweed's range in California. *Urophora quadrifasciata* arrived unaided and occurs throughout most of this weed's range. The two weevils generally infest more than 90% of seedheads,

and *B. fausti* tends to displace *L. minutus* at most sites over about a 6-year period. Squarrose knapweed populations have now declined to very low levels.

Insect biology

Agapeta zoegana, the sulfur knapweed moth (Leidoptera: Cochylidae), has one generation per year (Fig. 1). The short-lived adults are active at night during summer and early fall. White eggs are laid on knapweeds and nearby vegetation. Larvae crawl down and mine into the roots. The exposed sides of tunnels are covered with a silk web. Larvae persist through winter, and pupation occurs inside roots the following spring. This species does best at dry, well-drained, open sites that do not have dense vegetation.

Bangasternus fausti, the broad-nosed seedhead weevil (Coleoptera: Curculionidae), feeds on leaves and lays eggs on leaflets or stems close to flower buds (Fig. 2). The eggs are covered by a black anal excretion. Larvae tunnel up into the flower bud and consume the developing seeds. Pupation occurs inside the flower head, and adults emerge in late summer and disappear to hibernate in sheltered sites. Adults have a shorter snout than the two *Larinus* species.

Cyphocleonus achates, the knapweed root weevil (Coleoptera: Curculionidae), has one generation per year (Fig. 3). Adults feed on leaves and lay eggs in the root at the soil surface. Larvae feed inside the root and create a gall-like swelling. Larvae persist through the winter, and pupation occurs inside the root in the spring. Adults emerge in early summer and lay eggs throughout the summer.

Larinus minutus, the lesser knapweed flower weevil (Coleoptera: Curculionidae), feeds on leaves and lays eggs inside the flower head (Fig. 4). Larvae consume most or all of the developing seed and pupate inside the flower head. Adults emerge in the late summer and hibernate in sheltered sites. ***Larinus obtusus***, the blunt knapweed flower weevil, is very similar to *L. minutus,* but is a little larger.

Sphenoptera jugoslavica, the bronze knapweed root borer (Coleoptera: Curculionidae), lays eggs at the base of rosette leaves (Fig. 5). Larvae tunnel into the root and persist through winter, completing development in the spring. Pupation occurs inside the root, and adults emerge in mid-summer. Larvae have a swollen thorax and characteristic "J" shape.

Terellia virens, the green clearwing knapweed fly (Diptera: Tephritidae), lays eggs among the florets in open flower heads (Fig. 6). Larvae feed on developing seeds and overwinter inside the flowerheads. This insect has one generation per year.

Two tephritid flies form galls in the flower heads: the banded gall fly, ***Urophora affinis*** (Diptera: Tephritidae), has three faint parallel dark bands on its wings (Fig. 7) and the UV knapweed seedhead fly, ***U. quadrifasciata***, has a dark "UV" pattern on each wing (Fig. 8). Adults lay eggs in flower buds, and larvae convert an immature flower ovary into a gall. Multiple insects can develop inside one flower head. Two or more generations can occur during the summer, and larvae of the late summer generation remain in the flower head to hibernate until spring. *Urophora quadrifasciata* appears to be a better disperser, but *U. affinis* often displaces it after it arrives at a site. Both flies can be displaced by seed head weevils.

Biological control agents of knapweeds in California

Species	Common name	Host Attacked	Plant part attacked	Distribution	Impact	Notes
Agapeta zoegana	sulfur knapweed moth	spotted knapweed	roots	limited	low	first released in CA in 1993
Bangasternus fausti	broad-nosed knapweed seedhead weevil	spotted, diffuse, squarrose	seeds	widespread	high	first released in CA in 1994
Cyphocleonus achates	knapweed root weevil	spotted knapweed	roots	limited	low	first released in CA in 2001
Larinus minutus	lesser knapweed flower weevil	spotted, diffuse, squarrose	seeds	wide	high	first released in CA in 1995
Larinus obtusus	blunt knapweed flower weevil	meadow	seeds	limited	unknown	first released in CA in 1999
Sphenoptera jugoslavica	bronze knap-weed root borer	diffuse, squarrose	roots	wide	moderate	first released in CA in 1980
Terellia virens	green clearwing knapweed fly	spotted knapweed	seeds	limited	low	first released in CA in 1995
Urophora affinis	banded knapweed gall fly	spotted, diffuse, squarrose	flower gall	wide	moderate	first released in CA in 1976
Urophora quadrifasciata	UV knapweed seedhead fly	spotted, squarrose, meadow	flower gall	wide	low	initially spread into CA on its own, first recovered in 1990

How the Technique is Employed

Collect adult insects (flies and beetles) in the field by sweep net or aspirator; however, the root weevil will drop off the plant as soon as it sees you, and their camoflage coloring makes them extremely hard to find on the ground unless they move. Adult weevils can also be collected by holding an open container under them and allowing them to fall into it when they try to escape.

Adult sulfur knapweed moths can be collected in the evening by attracting them to a vertically hung sheet that is illuminated by bright light or black light.

The presence of insects can also be detected by opening mature flower heads or roots and looking for larvae and/or signs of damage.

For additional information see Winston et al. (2012) listed below.

Special Tips

It is not known where the seed head weevils overwinter, but it is likely in sheltered places, such as in tree bark, under rocks or in leaf litter. The seed head flies overwinter inside flower heads as larvae, and may be susceptible to predation by rodents, birds or goats eating flower heads.

Caveats

Knowing what insects are present may help you to integrate other management strategies. The flower head weevil species emerge in the late summer and overwinter as adults away from the plant. The seed head fly species overwinter inside flower heads as larvae. Thus, for example, fall grazing of flower heads by goats would kill most of the flies, but not affect the weevils.

Larinus minutus and *L. obtusus* have similar biologies and are very difficult to distinguish.

Where Can I Get These?

Some insects may be available from your county Agricultural Commissioner.

Some insects are commercially available through Integrated Weed Control (www.integratedweedcontrol.com) and Weed Busters Biocontrol (www.weedbustersbiocontrol.com).

Photographs

Figure 1. Left: The sulfur knapweed moth (*Agapeta zoegana*) adult. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org. Right: Larva inside root. Photo credit: USDA APHIS PPQ, Bugwood.org.

Figure 2. The broad-nosed seed head weevil (*Bangasternus fausti*) adult and black egg on stem below a flowerbud. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 3. The knapweed root weevil (*Cyphocleonus achates*) adult and larva inside root. Photo credit: Laura Parsons, University of Idaho, PSES, Bugwood.org.

Figure 4. Left: The lesser knapweed flower weevil (*Larinus minutus*) adult. Photo credit: L.L. Berry, Bugwood.org. Right: Exit hole in flower head. Photo credit: Gary Brown, USDA APHIS PPQ, Bugwood.org.

Figure 5. Left: The bronze knapweed root borer (*Sphenoptera jugoslavica*) adult. Photo credit: Norman E. Rees, USDA-ARS - Retired, Bugwood.org. Right: Larva inside root. Photo credit: University of Idaho, Bugwood.org.

Figure 6. The green clearwing knapweed fly (*Terellia virens*) female on flower bud. Photo credit: USDA APHIS PPQ, Bugwood.org.

Figure 7. The banded gall fly (*Urophora affinis*) female and galls in flower head. Photo credit: Jim Story, Montana State University, Bugwood.org.

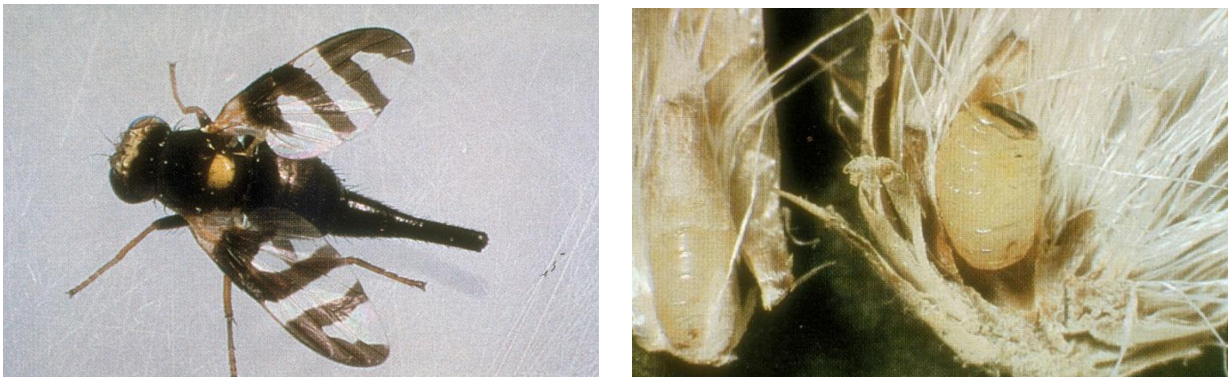

Figure 8. Left: The UV knapweed seed head fly (*Urophora quadrifasciata*) female. Photo credit: Jim Story, Montana State University, Bugwood.org. Right: Larvae in flower head. Photo credit: USDA-ARS, Bugwood.org.

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6.8 Mediterranean Sage (*Salvia aethiopus*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

One agent, Mediterranean sage root weevil (*Phrydiuchus tau*, Coleoptera: Curculionidae), has been introduced to the USA and is highly effective in California. It has one generation per year. Adults are in reproductive diapause during the summer and become active in the fall after rains start. Adults feed on rosette leaves and lay eggs on the undersides of basal leaves and in leaf axils. Eggs are protected by a fecal covering. Larvae tunnel down the leaf petioles to the center of the root where they feed and develop. Many larvae can develop inside one plant, and damage tends to reduce or prevent production of flower stems. Larger plants tend to be attacked more than small ones.

All life stages can be present on the plant during the winter. In the spring, mature larvae exit the plant and pupate in the soil. Adults emerge in late spring to early summer, and they feed briefly on the leaves and flower stalks before disappearing for summer aestivation, hiding in the soil under rocks or in other cool moist places. Adults are dark colored and have a small white "T" on their back. Adults can feed on other *Salvia* species, such as *S. sclarea*, and *S. verbenacea*, but larvae are known to completely develop only on Mediterranean sage. Larvae are susceptible to predation by ants when they emerge from the plant to pupate in the soil.

In California, CDFA scientists released a total of 2,600 weevils at 10 sites in Modoc county during 1976-1980, and 1,500 more weevils at 2 sites in Modoc county during 2002-2005. Surveys during 2005-2006 indicated low densities of Mediterranean sage at release sites that previously had high densities, and the weevils were present at undisturbed sites, but absent at roadside sites. It has been speculated that absence of weevils at the latter sites might be related to aggressive spraying of herbicides on roadside plants. The weevils were also found at locations far from known release sites, suggesting widespread dispersion of this agent. No impacts on nontarget plants have been reported.

Biological control agents of Mediterranean Sage

Species	Common name	Distribution	Impact	Notes
Phrydiuchus tau	root weevil	wide	high	first released in CA in 1976

How the Technique is Employed

Some biological control agents are likely to already be present at your site. Look for signs of insects: ragged adult feeding holes on leaves in the fall and winter, or late spring and early summer. Presence of larvae and feeding damage inside upper roots during winter and early spring. Collect adult weevils in the field by sweep net or hand collecting. Adults have a white "T" on their back and make a chirping sound when disturbed.

Special Tips

Knowing that insects are present may help you to integrate other management strategies. The adult weevils emerge in the early summer and are inactive during most of summer and fall. This is a good time of year to apply alternate control methods, if desired.

The root weevil will multiply if it has suitable habitat, and adults have safe over-summering sites. Avoid causing drastic fluctuations in the Mediterranean sage population from year-to-year that would cause the weevil population to crash. For example, it would be better to use a treatment such as herbicides or other non-chemical methods to control the periphery of an infestation and let the biological control agents multiply in the center of the weed infestation.

Caveats

Herbicides that kill Mediterranean sage during the winter or early spring, before larvae emerge, will reduce the weevil population, and disrupt biological control.

Areas where herbicides are used regularly, such as road shoulders, appear to prevent establishment of the biological control agent.

Where Can I Get These?

You can collect adult weevils in the field by sweep net or hand collecting. Insects may also be available from your county Agricultural Commissioner.

Photographs

Figure 1. Left: Mediterranean sage root weevil adult (*Phrydiuchus tau*) with feeding damage on leaf. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org. Right: Larvae in root crown. Photo credit: L.L. Berry, Bugwood.org.

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6.9 Musk/Italian/Milk Thistles (*Carduus nutans, C. pycnocephalus, Silybum marianum*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Musk (*Carduus nutans*), Italian (*C. pycnocephalus*), and milk (*Silybum marianum*) thistles are hosts of a small suite of biological control agents. In total, five species of insects have been approved for release by USDA-APHIS: the seed head weevil *Rhinocyllus conicus* (Curculionidae: Coleoptera), the root weevil *Trichosirocalus horridus* (Curculionidae: Coleoptera), the rosette beetle *Psylliodes chalcomera* (Chrysomelidae: Coleoptera), the seed head fly *Urophora solstitialis* (Tephritidae; Diptera), and the stem fly *Cheilosia grossa* (Syrphidae: Diptera). However, **none of these species are currently permitted for use in California** because of risks to nontarget native plants. Some of these agents were approved by APHIS at a time when there was little concern about native species, and they would not meet current standards (Hinz et al. 2014). APHIS has revoked the permit for the seed head weevil.

In California, only the seed head weevil was intentionally released, and it occurs wherever musk thistle is found. The stem fly moved into California on its own and is limited to thistle populations in central Siskiyou County. The root weevil is established in many states, but it has not been reported in California. The rosette beetle and the seed head fly are not known to be established in the USA. In addition, an exotic rust, *Puccinia carduorum* (Uredinales: Pucciniaceae), which was intentionally introduced under an experimental use permit as a classical biological control agent in Maryland in 1987, eventually spread on its own into California and now occurs wherever musk thistle is known to occur.

The seed head weevil deposits eggs on young flower heads, and the larvae burrow into the head and feed on the developing seeds (Piper and Coombs 2004b; Fig. 1). It has one generation per year and overwinters as an adult. High populations of the weevil can reduce seed production by up to 80% in musk thistle and 60% in Italian thistle, but usually less than 20% in milk thistle. Following its release in California this weevil has been found to attack at least 12 species of native thistle (*Cirsium* spp.) (Turner et al. 1987). In California, the weevil emerges from winter diapause before many of the native thistle species begin flower production, and this asynchrony limits the amount of seed loss due to the weevil (Goeden and Ricker 1985, Herr 2000). However, on a national level, this weevil has attacked at least 22 species of native thistles, including causing significant damage to a federally threatened plant species (*Cirsium pitcheri*) (Pemberton 2000, Louda *et al.* 2005, Hinz *et al.* 2014). It also attacks thistle species in several other genera, including *Carduus*, *Onopordum*, and *Silybum*, all of which are alien to North America.

The stem fly emerges in the early spring and lays eggs in the growing tip of the young bolt growing from the rosette (Piper and Coombs 2004a; Fig. 2). Larvae mine the elongating flowering stem during the summer and fall. Pupation occurs in the lower stem near the root crown and lasts through the winter. In California, the stem fly has been found inside musk thistle, Italian thistle, and bull thistle.

The rust has a complicated life cycle with five life stages (Littlefield *et al.* 2004; Fig. 3). It is known to infect only musk thistle. The rust produces resting spores that resist cold temperatures during winter.

Resting spores germinate in the spring and produce secondary spores that infect plants. Optimal conditions for infection are cool (65-70°F) and humid (at least 8 hours of dew). Infected plants produce pustules in about 2 weeks, which release spores that disperse in the wind. Infection cycles can repeat during the summer, and resting spores are produced when plants senesce in autumn.

Biological control agents of musk, Italian, and milk thistle

Species	Common name	Host plant	Distribu-tion	Impact	Notes
Cheilosia grossa [=*C. corydon*]	stem fly	musk thistle Italian thistle (bull thistle)	limited	unknown	Moved into CA on its own, first obs. in 2015; not a permitted agent
Puccinia carduorum	musk thistle rust	musk thistle	wide	limited	Moved into CA on its own, first obs. in 1998; not a permitted agent
Rhinocyllus conicus	seed head weevil	musk thistle Italian thistle milk thistle and other thistles	wide	moderate to high	First released in CA in 1969; not a permitted agent

How the Technique is Employed

The only organism that is known to cause significant damage to populations of these target weeds in California is the seed head weevil, *R. conicus*, which is not a permitted agent. It is widespread and occurs on almost all stands of musk and Italian thistles. Its presence on milk thistle is patchy, and when found, occurs in lower numbers.

No organisms are permitted for use as biological control agents; however, control methods that complement the seed head weevil damage, such as encouraging competitive vegetation and treating weeds from the periphery of the infestation inward, would work best to control thistle populations.

For additional information, see Winston et al. (2012).

Special Tips

The seed head weevil has performed best in the musk thistle populations found in Siskiyou County where it provides good control of musk thistle. In this area, musk thistle populations usually erupt following disturbance, such as clear cutting of forest plantations. The seed weevil then builds up its populations, and over the next several years causes a steady decline in musk thistle plants. Observations in the Sierra Nevada Mountains near Truckee in Nevada County suggest that weevil populations occur at lower levels (<50%) so the ability of the weevil to reduce musk thistle abundance can vary regionally.

The seed head weevil is present in plants throughout most of the year. Adult weevils emerge in June and are active visiting flower heads in July and August while larvae are present inside seed heads during the other ten months. Dead plants with seed heads laying on the ground have live weevil larvae in the heads, so leaving them in place will likely lead to higher weevil numbers. If the goal is to eradicate musk

thistle at the site and protect nearby native thistles from the weevil, then destroy mature seedheads, or use herbicides to prevent their formation.

Caveats

The seed head weevil has been observed feeding on over 20 native *Cirsium* species in the U.S. Larvae of the stem fly*, C. grossa*, have been found inside the exotic thistle *Cirsium vulgare* but no native *Cirsium* species to date. There has been no non-target infection by the rust.

Where Can I Get These?

None of the biological control agents for musk, Italian or milk thistle are permitted for use in California.

Photographs:

Figure 1. Left: Thistle seed head weevil (*Rhinocyllus conicus*) adult. Photo credit: Baldo Villegas, CDFA. Center: Eggs on flower bud. Photo credit: Baldo Villegas, CDFA. Right: Larvae and damage. Photo credit: C.E. Turner, USDA-ARS.

Figure 2. Left: Thistle stem fly (*Cheilosia grossa*) adult, side view. Photo credit: Martin Hauser, CDFA. Center: Larvae in stem. Photo credit: L. Smith, USDA-ARS. Right: Adult, top view. Photo credit: Martin Hauser, CDFA.

Figure 3. Thistle rust (*Puccinia carduorum*). Photo credit: Baldo Villegas, CDFA.

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6.10 Puncturevine (*Tribulus terrestris*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Two insects, the seed weevil (*Microlarinus lareynii*, Coleoptera: Curculionidae) and the stem weevil (*M. lypriformis*), have been introduced as biological control agents in California and are highly effective in reducing puncturevine.

These two weevils look very similar but attack different parts of the weed. Both species have multiple generations during the summer. Adults hibernate during the winter, hiding in surface vegetation and leaf litter. The seed weevil has a shorter proboscis (Figs. 1 & 2).

The seed weevil deposits eggs in holes chewed in the sides of immature fruits and covers them with a black secretion. Larvae feed on developing seeds and pupate inside the fruit. Adults emerge through an exit hole and feed on stems, leaves, flowers, buds, and fruits.

The stem weevil deposits eggs in the root crown or in the underside of stems. Larvae feed inside the stems and roots, where they pupate. Emerging adults leave exit holes in the stems.

Adults of both species cause minor defoliation, but larval damage to seeds and stems can be significant. For example, seed production decreased by 46% within 5 years after the first release in southern CA, and puncturevine coverage decreased by 70% to 100% in 5 of 6 regions studied during 15 years (Huffaker et al. 1983). Impact appears to be higher at non-irrigated sites, or when there is less precipitation. These weevils have substantially reduced the weed population in many areas of California and have been highly effective in Hawaii. However, it has been difficult to establish them at higher elevations and latitudes, presumably because of the negative effect of cold winter temperatures on adult survival. For example, the seed weevil established at only 1 of 5 sites where it was released in Lassen county, and the stem weevil failed to establish at any of these sites (Villegas and Gibbs 2010).

Larvae of the seed and stem weevils have been observed on Arizona poppy (*Kallstroemia grandiflora*) in Arizona, but no substantial non-target damage in the field has been reported.

Biological control agents of Puncturevine

Species	Common name	Distribution	Impact	Notes
Microlarinus lareynii	seed weevil	moderate	high	First released in 1961 in CA
Microlarinus lypriformis	stem weevil	moderate	high	First released in 1961 in CA

How the Technique is Employed

Some biological control agents are likely to be present at your site. Look for signs of weevils: adult feeding holes on leaves, stems, and fruits. Presence of larvae and feeding damage inside fruits and stems. If they are present, then there is no need to release additional insects.

Collect adult weevils in the field by vacuuming or hand collecting them from underneath plants. Infested plants and associated litter can be put in a paper bag and held to allow adults to emerge. Placing the bag in the sun for a short time to heat up stimulates adults to climb up the sides, making it easy to collect them.

Note that parasitic and predatory insects attack both species of weevils, so be carefult to collect only the adult weevils to release at another location to avoid spreading their natural enemies.

Special Tips

Weevils overwinter in leaf litter and other vegetation or debris, and under tree bark. Adults can live for long periods feeding on other plant species to survive, but they can only lay eggs after feeding on puncturevine and its close relatives, such as *Kallstroemia* species.

Biological control is probably most effective at areas that are dry and undisturbed (e.g., too difficult to access or too environmentally sensitive to treat with herbicides).

The adult weevils appear in the early summer on young puncturevine plants, and they stop reproducing in late summer and fall. Try to apply alternate control methods, if desired, at times of the year when insects are not on the plants.

Caveats

The seed and stem weevils do not successfully overwinter north of Sacramento, so other methods should be applied there. Good level of control by these weevils occurs south of Sacramento.

Herbicides or other methods that kill puncturevine during summer will reduce the weevil population and disrupt biological control, but adults should be able to disperse and search for nearby plants that have not been treated.

Where Can I Get These?

Insects may be available from your county Agricultural Commissioner or CDFA.

Photographs

Figure 1. Left: Puncturevine seed weevil (*Microlarinus lareynii*) adult. Photo credit: M.S. Caterino/SBMNH, BugGuide.net. Right: Larva in seed pod. Photo credit: Baldo Villegas, CDFA.

Figure 2. Left: Puncturevine stem weevil (*Microlarinus lypriformis*) adult. Photo credit: Jason Botz, BugGuide.net. Center: Exit holes. Photo credit: Baldo Villegas, CDFA. Right: Larva in stem. Photo credit: Baldo Villegas, CDFA.

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6.11 Purple Loosestrife (*Lythrum salicaria*)

Lead authors: Dr. Fritzi Grevstad, Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Four insect agents have been released in the USA, at least one of which (the leaf beetle *Galerucella calmariensis*) is established in California.

Biological control research initially focused on the northern states, where these agents have been very successful at establishing, multiplying, and dispersing. Purple loosestrife biomass has been reduced by more than 95% at some sites, but this has often taken more than 10 years. The biological control agents originate from northern Europe. Recent studies that model adaptation of insect life cycles to seasonal temperature and day length indicate that some species are not well adapted to more southerly locations, including much of California, because they enter winter diapause too soon (Grevstad and Coop 2015).

The two leaf beetles (*Galerucella calmariensis* and *G. pusilla*, Coleoptera: Chrysomelidae) look very similar and have similar life histories (Figs. 1 & 2). Adults overwinter in soil and vegetation near purple loosestrife plants and emerge from hibernation in the spring when purple loosestrife begins to grow. Adults feed on leaves, forming characteristic 'shot holes.' Eggs are laid on leaves and stems. Small larvae feed inside leaf or flower buds, and larger larvae feed on leaves forming transparent 'windowpanes' (Fig. 1B). Pupation occurs in the soil, or inside the stems when plants are in standing water. These species can have one to three generations per year, depending on latitude and temperature. High densities of larvae can completely defoliate plants. Damage reduces plant growth and seed production. Adults are good dispersers and can find host plants up to 0.6 miles away. Although both species have been released widely in California, only *G. calmariensis* is known to have established, and only in areas north of Butte County (Fig. 5). The level of control is excellent in Shasta, but low in Butte and Siskiyou counties.

The root weevil (*Hylobius transversovittatus*, Coleoptera: Curculionidae) overwinters as an adult and is active from the time the host plants start growing until September (Fig. 3). Adults are primarily nocturnal and feed on leaves and stems. Eggs are laid in stems or nearby in the soil. Larvae mine into the roots and take 1-2 years to develop, depending on temperature and the time of oviposition. Pupation occurs inside the upper root, and adults emerge from June to October. Adults can live more than one year. The principal impact is caused by larval damage to the roots which reduces plant growth and reproduction and can ultimately kill plants. In Europe, the weevil occurs at all purple loosestrife habitats except those that are permanently flooded. Both adults and larvae can survive extended periods under water, but summer flooding prevents adults from laying eggs. This species has been released at sites in California, but establishment status is unknown.

The seed weevil (*Nanophyes marmoratus*, Coleoptera: Nanophyidae) overwinters as an adult (Fig. 4). In spring, adults feed on young leaves and then move to the flower spikes where they feed on flower buds. Eggs are laid in flower buds, and oviposition continues into August. Larvae feed inside the developing flower buds, which fail to open or produce seed, and adults emerge in the late summer. The weevil has

one generation per year. Feeding damage by the adults and larvae directly reduces seed production. This species has been released at sites in California, but establishment status is unknown.

Biological control agents of purple loosestrife

Species	Common name	Distribution	Impact	Notes
Galerucella calmariensis[2]	black-margined loosestrife beetle	wide in northern CA	high in northern CA	First released in 1998 in CA
Galerucella pusilla[2]	golden loosestrife beetle	not recovered in CA	unknown	First released in 1998 in CA
Hylobius transversovittatus	loosestrife root weevil	unknown in CA	unknown	First released in 1996 in CA
Nanophyes marmoratus	loosestrife seed weevil	unknown in CA	unknown	First released in 1997 in CA

How the Technique is Employed

Adult leaf beetles can be collected by sweep net or by beating plants with a stick to knock them off onto a collecting cloth or funnel held below for redistribution.

Adult root weevils, which are nocturnal, can be hand collected at night or in the early morning near sunrise for redistribution. Look for dark green inky droppings and feeding on lower leaves (uniform removal of tissue along leaf edges) (Fig. 3B). Larvae can be reared on artificial diet.

Collect adult seed weevils by sweep net or by beating plants with a stick above a collecting cloth.

For additional information see Blossey *et al.* (2015).

Special Tips

Collecting adults of these agents and releasing them on purple loosestrife populations that do not seem to be heavily infested may increase control.

Caveats

California is further south than the natural latitude of these insects, and it is not clear how well they will adapt to this difference. It would be better to obtain insects from California than from other states further north because they may be better adapted to our low latitude.

The leaf beetles may attack crepe myrtle (*Lagerstroemia indica*) and ornamental rose bushes that are near heavily infested purple loosestrife, but this ends after beetle populations decrease.

Biological control appears to be more successful at sites with low soil fertility, and in the presence of competing vegetation.

Successful biological control of purple loosestrife may result in increases of other invasive species such as reed canary grass (*Phalaris arundinacea*) and the European variety of common reed (*Phragmites australis*).

Continuously flooded sites are not suitable for the leaf beetles or root weevils.

Seed weevils are probably more successful where the leaf beetles are absent.

High summer temperatures and short summer photoperiod limit how far south *G. calmariensis* can survive. Because all releases south of Butte County failed to establish, it is recommended that releases of *G. calmariensis* occur from Butte County north.

Where Can I Get These?

Contact CDFA or your local Agricultural Commissioner to see if they can provide insects. These insects are available from two commercial vendors in Montana: Integrated Weed Control (www.integratedweedcontrol.com) and Weed Busters Biocontrol (www.weedbustersbiocontrol.com).

Photographs

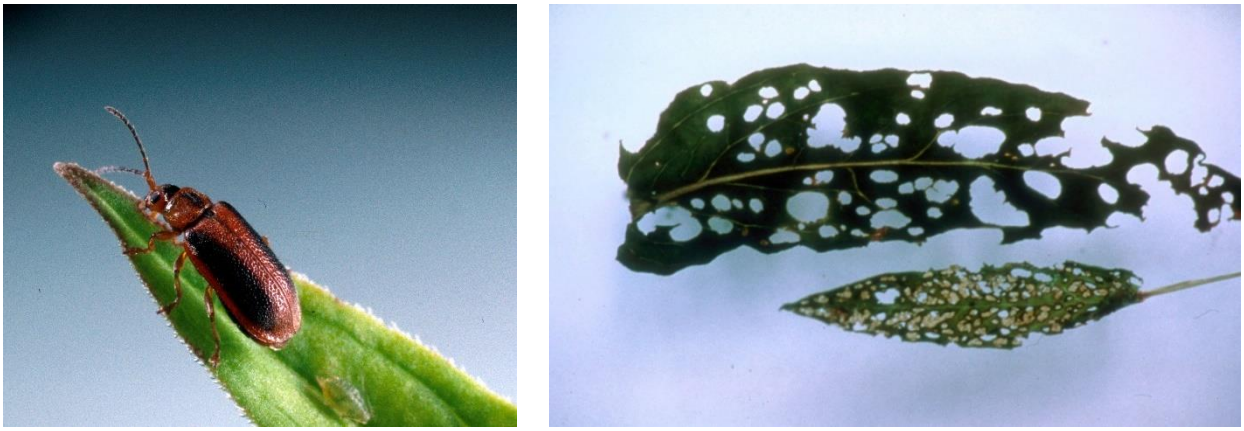

Figure 1. Left: Black-margined loosestrife beetle (*Galerucella calmariensis*) adult. Photo credit: Mark Schwarzlander, University of Idaho, Bugwood.org. Right: Larval feeding damage. Photo credit: Bernd Blossey, Cornell University, Bugwood.org.

Figure 2. Golden loosestrife beetle (*Galerucella pusilla*). Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 3. Purple loosestrife root weevil (*Hylobius transversovittatus*) adult and adult feeding damage. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 4. Purple loosestrife seed weevil (*Nanophyes marmoratus*). Photo credit: Tom Murray, Bugguide.

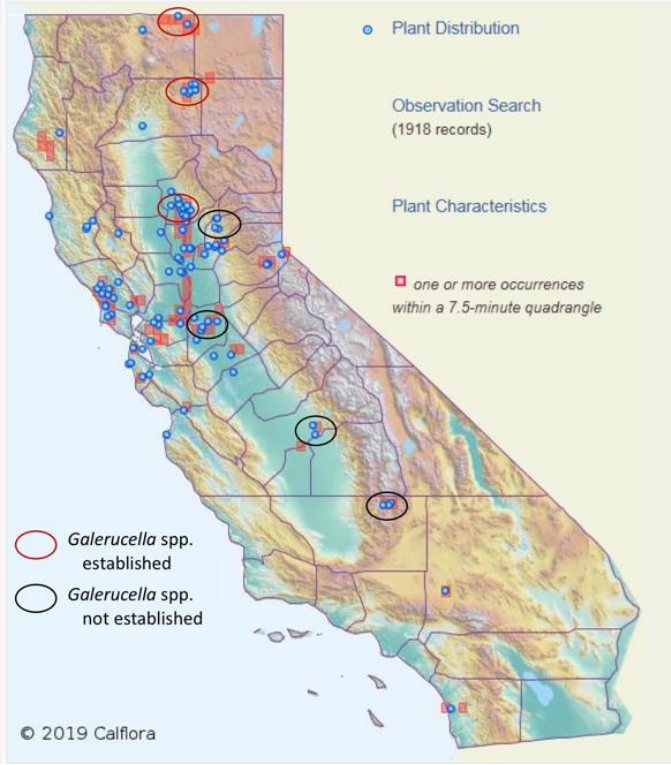

Figure 5. Map of CDFA releases and establishment of the Galerucella spp. beetles in California. Plant distribution map from Calflora.org. Blue dot = purple loosestrife observation in Calflora; red squares = multiple records of purple loosestrife in Calflora within 7.5-minute quadrangles.

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6.12 Rush Skeletonweed (*Chondrilla juncea*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Four agents have been released in California, and at least three of them have become established: a gall midge, a gall mite, and a rust fungus pathogen. The fungus and the gall mite appear to have the most impact, although the latter is often limited by naturally occurring predators. The root moth was first released in 2014 but has not been recovered at its release sites. The weed is generally well controlled in California by biological control agents. No non-target plants appear to be at risk of attack.

Gall mites (*Aceria chondrillae*, Acari: Eriophyidae) are microscopic and can be seen at 20x magnification. Females form galls on axillary and terminal plant buds in which hundreds of larvae can develop (Fig. 1). Mites develop rapidly (in 10 or more days) and can have many generations per year. They probably disperse by wind, like pollen. Mite infestation reduces plant vigor and reproduction, and high infestations can kill young plants. Adults overwinter in rosette shoot buds. Mites are most successful at warm sites (southern or southwestern exposure) with well-drained soil and little soil disturbance (not on cultivated croplands). The mites tolerate high summer temperatures (95°F), but severe winter conditions in Idaho appear to reduce survival. Predaceous mites that feed on gall mites can limit their effectiveness.

Larvae of **the root moth** (*Bradyrrhoa gilveolella,* Lepidoptera: Pyralidae) eat internally and externally on the roots and hide in tunnels comprised of silk, frass, and soil particles (Fig. 2). There are 1 to 2 generations per year in Oregon. In Europe, adults emerge in May to June and August to October. Larval damage exposes roots to soil pathogens, and attack by multiple larvae can kill aboveground plant parts.

Larvae of **the gall midge** (*Cystiphora schmidti*, Diptera: Cecidomyiidae) develop inside small galls ($^1/_8$ - inch diameter) on the leaves and stem (Fig. 3). Pupation occurs inside the galls or on the soil surface. There are 4 to 5 generations per year. Adults are active from April to October. Infestation reduces plant growth and reproduction, and high infestations can cause plants to die. Gall midges are most abundant where the average yearly temperature is higher than 63°F and precipitation is less than 400 mm (16 inches). Heaviest attacks occur at open locations with well-drained soil. Note that native parasitoids have greatly reduced effectiveness of this agent in California.

The rust fungus (*Puccinia chondrillina*, Uredinales: Pucciniaceae) develops on leaves and stems creating pustules that release spores (Fig. 4). Infection reduces plant vigor, reproduction, and survival. Infection of rosettes in fall and spring often kills plants. The rust appears to be effective on 2 of the 3 biotypes of rush skeletonweed in the USA, including the one known to occur in California. It develops best at more humid sites. In a field experiment, infested plants had 89% less biomass and produced 94% fewer seeds than uninfested plants, and 65% of plants died prematurely (Emge *et al.* 1981).

At three field sites in central California, the combined impact of the three biological control agents (gall midge, gall mite and rust pathogen) reduced the density of skeletonweed plants between 56% and 87% (Supkoff *et al.* 1988).

Biological control agents of rush skeletonweed

Species	Common name	Distribution	Impact	Notes
Aceria chondrillae	gall mite	Wide	medium	First released in CA in 1977
Bradyrrhoa gilveolella	root moth	not recovered in CA	unknown	First released in CA in 2014
Cystiphora schmidti	gall midge	wide	low	First released in CA in 1975
Puccinia chondrillina	rust fungus	wide	high	First released in Ca in 1976

How the Technique is Employed

Some biological control agents are likely to be present at your site. Look for signs of their damage. Gall mites distort the flower buds into gall tissue (Fig. 1). The root moth larvae produce tunnel damage in the roots (Fig. 2). The gall midge produces lumps on stems and leaves (Fig. 3). The rust fungus produces rust-colored clumps of spores on leaves (Fig. 4).

For the gall mite, collect galled stems July to October. and place them in direct contact with target plants so that mites can crawl onto them. Galled stems can be refrigerated for up to several weeks before releasing mites.

Root moth adults can be collected by sweep net during the evening in May to June; keep them cool and release them as soon as possible.

For the gall midge, collect galled stems from early July to late September. Remove seed heads and flowers to prevent distributing seed. Tie the stems together to form a tipi and place them among the target plants so that adults can emerge and lay eggs. Note that this method may inadvertently introduce native parasitoids, which have greatly reduced effectiveness of this agent. It would be best to allow the insects to emerge inside a cage and then separate the midges from parasitoids (Hymenoptera) so that only midges are released.

Rusted stems can be collected in summer and placed at target sites to release teliospores in the fall. Spore germination requires a long dew period (8-16 hours), so cool humid evenings are optimal. Rosettes with pustules (uredia) can be dug up and transplanted to target sites in spring or fall.

For more details, see Milan *et al.* (2016).

Special Tips

None.

Caveats

Rush skeletonweed has least three different biotypes in North America that vary in resistance to the mite and the rust fungus. All known biotypes in California are susceptible to the mite and to the rust.

Native natural enemies have limited the effectiveness of the gall midge (parasitoids) and the gall mite (predatory mites). Transferring galled plant material can easily transfer these natural enemies, if they are present, so this should not be done.

A naturally occurring parasitic fungal disease has been reported to reduce effectiveness of the rust fungus (*P. chondrillina*) in Idaho. Therefore, do not bring rush skeletonweed plant material from other states to prevent introduction of other plant diseases that may interfere with effective biological control in California.

Where Can I Get These?

Some agents may be available from your county Agricultural Commissioner.

Photographs

Figure 1. Left: Rush skeletonweed flower buds damaged by the gall mite (*Aceria chondrillae*). Photo credits: Gary L. Piper, Washington State University, Bugwood.org. Inset: Scanning electron micrograph of a mite. Photo credit: Charles Turner USDA-ARS, Bugwood.org. Right: Rush skeletonweed gall mite damage. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 2. Rush skeletonweed root moth (*Bradyrrhoa gilveolella*) adult and larva. Photo credit: Mark Schwarzländer, University of Idaho, Bugwood.org

Figure 3. Left: Rush skeletonweed gall midge (*Cystiphora schmidti*) adult. Photo credit: Gary L. Piper, Washington State University, Bugwood.org. Right: Galls on stems and leaves. Photo credit: Baldo Villegas, CDFA.

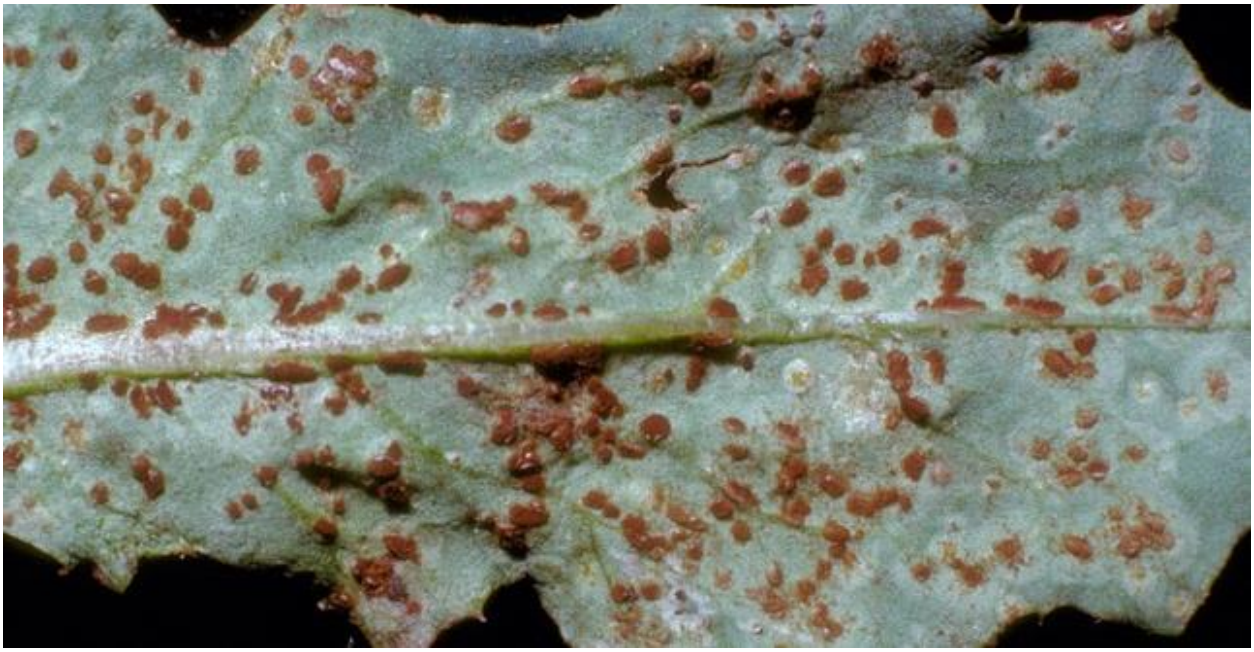

Figure 4. Rush skeletonweed rust fungus (*Puccinia chondrillina*). Photo credit: Gary L. Piper, Washington State University, Bugwood.org.

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6.13 Russian Knapweed (*Acroptilon repens*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Russian knapweed has two approved biological control agents in California: the gall wasp, *Aulacidea acroptilonica* (Hymenoptera: Cynipidae), and the gall fly, *Jaapiella ivannkovi* (Diptera: Cecidomyiidae). The stem gall nematode (*Subanguina picridis*) has been released in some other states, but is not very effective, and is not permitted for release in California.

The gall wasp has one generation per year. Adults appear in the spring when plants are emerging from the soil (Fig. 1). About 90% of the insects are female, but adults live for only about 5 days (range 2 to 9 days). Females deposit eggs in the young growing stems, and the hatched larvae cause the formation of a stem gall. Larvae remain inside the gall all winter, and adults emerge from exit holes the following spring. The gall wasp has established good populations at several locations in Lassen County and at least one location in Siskiyou County. Efforts are now underway to release the gall wasp on Russian knapweed infestations throughout California, especially the San Joaquin Valley. Galled plants produce few flowers and fewer seeds. Post-release monitoring in 2019 showed that the gall wasp caused a 66% and 85% decline in seed production at sites in Lassen and Siskiyou County, respectively.

The adult female **gall fly** deposits eggs on buds at the tip of stems, and the larvae induce the formation of a 'rosette gall' comprised of stunted shoot and bunched leaves at the stem tip (Fig. 2). Up to 14 larvae can occur inside one gall. Adult gall flies emerge in spring when the plants are emerging from the roots. Adults live for about 3 days (range (2 to 7 days), and the sex ratio is 1:1. There are multiple generations each year, with the last generation overwintering as larvae in the galls. Despite releases of several hundred insects from 2011 through 2015, the gall fly has not established in California. This is due, in part, to the fly's requirement for a second generation in summer. In California, Russian knapweed plants stop growing in June or July due to lack of moisture, and the absence of new growth in the summer causes the gall fly to die out because it is unable to form galls.

Biological control agents of Russian knapweed

Species	Common name	Distribution	Impact	Notes
Aulacidea acroptilonica	gall wasp	limited	moderate	First released in CA in 2014
Jaapiella ivannkovi	gall fly	failed to establish	none	First released in CA in 2011

How the Technique is Employed

Galls can be collected in later winter or early spring and moved to new field sites. However, at the release site in Siskiyou County, overwintering gall wasp larvae experienced an infestation rate of 9% by local parasitoids (parasitic wasps). It is best to not move parasitoids to new release sites, so collect galls from field sites in early spring and hold them indoors for adult wasps to emerge. The parasitoids, which

are cigar-shaped, have a greenish sheen and are slightly smaller, usually emerge a week before the gall wasps, which are larger and have shiny black, more bulbous abdomens. The gall wasp needs young growing plants to produce galls, so timing of the release is critical. Establishment success is highest in early spring when plants are between 1 to 5 inches in height. Once a plant has reached full height and begins to flower, the plant is no longer putting out new growth, and it is too late for the wasp to initiate gall formation. The best time for release is March for plants in the San Joaquin Valley and April for plants in northern California. The gall wasp should be released where immediate eradication of Russian knapweed populations is not the primary objective.

Special Tips

Russian knapweed is a common pest of pastures and grazing lands; however, cattle destroy the galls during grazing, and the gall wasp does not persist. Fencing a small area within a pasture to prevent grazing has allowed the gall wasp to establish and build up populations quickly.

The gall wasp is present in plants throughout the year. Adult gall wasps emerge in early spring and are active visiting young growing shoots in March (central California) and April (northern California), while larvae are present inside stem galls during the other ten months. Dead plants with galls laying on the ground have live gall wasp larvae, so it is best not to remove these plants until adults have finished emergence.

Caveats

Herbicides that kill Russian knapweed plants are usually applied during early spring when adult wasps are active. It is best not to use herbicides where the gall wasp is released and being relied upon to control plants. Note that the biological control agent will probably not establish in areas where herbicides are used regularly, such as road shoulders.

Grazing can also impact the effectiveness of gall wasps (see Special Tips).

Where Can I Get These?

This gall wasp is a part of a new distribution program by the California Department of Food and Agriculture (CDFA) and is available depending on supply. To obtain insects for release contact your local Agricultural Commissioner who will contact CDFA and request for a release.

To date, there are no known commercial vendors of the gall wasp.

Photographs

Figure 1. Left top: Gall wasp (*Aulacidea acroptilonica*) adult female. Photo credit: Joel Price, Oregon Department of Agriculture. Left bottom: Gall wasp adult and emergence holes. Photo credit: Viola Popescu, CDFA. Right: Gall wasp stem galls. Photo credit: Michael J. Pitcairn, CDFA.

Figure 2. Gall fly (*Jaapiella ivannkovi*) females lay eggs in shoot tips and 'rosette galls' form at the ends of stems, stunting growth. Photo credits: Jeffrey Littlefield, Montana State University.

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6.14 Scotch Broom (*Cytisus scoparius*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Scotch broom has two approved biological control agents in California: the stem moth, *Leucoptera spartifoliella* (Lepidoptera: Lyonetiidae), and the pod weevil, *Exapion* [=*Apion*] *fuscirostre* (Coleoptera: Brentidae). The pod weevil is widespread in California and occurs wherever Scotch broom is found. The stem moth is also widespread, but its abundance is generally low and patchy. Recently, two other natural enemies have moved into California, apparently on their own: the gall mite, *Aceria genistae* (Eriophyidae: Acari) and the seed beetle, *Bruchidius villosus* (Coleoptera: Bruchidae).

The stem moth lays eggs on the green stems after bloom in the spring (Fig. 1). The larvae burrow into the stem and tunnel up and down the length of the stem to feed. Larvae overwinter in the stem and leave their tunnels in spring to pupate, spinning a white cocoon attached to the stem ridges. The stem moth usually occurs in low numbers which appears to cause little damage in California. On occasion, when large numbers do occur and stem die back is observed, plants usually regrow from below the damage.

The pod weevil has one generation per year. Adults emerge from overwintering when broom is in flower and feed on Scotch broom stems, flower petals and pollen (Fig. 2). Later, when the pods form and the seeds begin to swell, the female chews a hole in the pod and deposits an egg on on individual seeds. Upon hatching, the larva burrows into the developing seed and consumes it from inside. Eggs may be deposited on several seeds within a pod. The resulting larvae develop to adults in the pod and leave when the mature pod splits open in summer. Adults are inactive during the summer, fall and winter, hiding in sheltered sites off the plant. Weevils infest about 60% of pods, on average, which results in destruction of 30 to 40% of viable Scotch broom seed in California.

The gall mite is an accidental introduction that was first discovered in Washington State and has spread south into California on its own (Pratt *et al.* 2019). It is most common on Scotch broom growing in the foothills of the Sierra Nevada Mountains. The occurrence of the gall mite is variable, with some plants being heavily infested with galls while other plants nearby have only a handful of galls (Fig. 3). In some patches, almost all plants are galled, but in other patches, only one or two plants have just a couple of galls. As this is a new organism in California, the population levels are continuing to increase in abundance. Galls form in young flower and leaf buds, and high densities cause extensive stem die-back and prevent flower production. The mites are microscopic and are visible at 20x magification. The galls are 0.2 to 1.2 inches in diameter and are hairy in appearance. The number of generations is unknown but preliminary observations suggest that mites leave galls to infest new plants in June and hide under bud scales until the following spring. Mite dispersal is typically by blowing in the wind (like pollen). Host specificity of the mite is currently being evaluated by Dr. Paul Pratt, USDA Agricultural Research Service in Albany, CA. Field surveys to date have not found it on any native species.

The seed beetle was accidentally introduced in the eastern USA before 1919. The State of Oregon obtained a permit to move it from North Carolina into Oregon and introduced it starting in 1998. The

beetle has been spreading on its own from Oregon south into California. It was first discovered in Siskiyou County in 2014 and has increased and spread steadily southward. It is now found in Marin County in the Coast Range, in El Dorado County in the Sierra Nevada Mountains, and everywhere in between. The seed beetle also has been observed in pods of French broom, *Genista monspessulana*, but at a much lower level than in Scotch broom. However, given its rapid spread, it is likely that the seed beetle uses French broom as a bridge between isolated Scotch broom populations. The seed beetle is still expanding southward into California, and how far south it will spread is unknown. French broom populations extend further south into California than Scotch broom, and it is not known if the seed beetle will continue to move south following the French broom. Given that the pod weevil and the seed beetle exploit the same resource, it is not known how the two will interact: will they combine to increase the overall destruction of seed, or will the seed beetle simply replace the pod weevil so that the combined impact is unchanged? It is still too early to determine the outcome.

The seed beetle has one generation per year (Fig. 4). Adult females deposit their eggs on the outside of the young green seed pod in May. The egg hatches, and the larva burrows into the pod and into a seed where it feeds. Each larva completes its development within one seed. Adults emerge from the seeds and wait inside the pods until they open in summer. The seed beetle now occurs wherever Scotch broom occurs in California. Surveys in California have found the seed beetle to destroy over 60% of seed at some locations. The seed beetle has been observed to develop on some nontarget species in the field in France and New Zealand, including a native California lupine (*Lupinus arboreus*) and a forage species (tree lucerne, *Cytisus proliferus* [= *Chamaecytisus palmensis*]) (Sheppard et al. 2006, Haines et al. 2007), and it is not likely to be permitted in the future.

Both the gall mite and the seed beetle are **not** permitted for use as biological control agents in California because their risk to nontarget species has not been fully evaluated.

Biological control agents of Scotch broom

Species	Common name	Distribution	Impact	Notes
Leucoptera spartifoliella	stem moth	wide	low	First released in CA in 1960
Exapion fuscirostre	pod weevil	wide	moderate	First released in CA in 1964
Aceria genistae	Scotch broom gall mite	wide	unknown	Accidental introduction, found in CA in 2014. Not a permitted agent.
Bruchidius villosus	seed beetle	wide	high	Accidental introduction, found in CA in 2014. Not a permitted agent.

How the Technique is Employed

Of the permitted insects, the pod weevil provides the highest impact through direct destruction of seed. The pod weevil can be found by breaking open mature (black) pods and looking for adult weevils among

the seeds. Adult females can be seen crawling on the green pods in May, and the empty eggshells remain on the outside of the pods for several weeks and can be seen with careful observation. It occurs wherever Scotch broom occurs in California.

The stem moth has too little impact in California to be recommended for use as a control organism.

See additional details in Andreas et al. (2017).

Special Tips

The pod weevil is present in plants from March through July. Adult weevils emerge from split pods in summer and are away from the plant until flowering in the spring.

Pod weevil larvae damage the inside and outside of seeds, which helps to distinguish them from seed beetle larvae, which feed completely inside a seed. Adult pod weevils have longer snouts and wing covers (elytra) than the seed beetles.

Recent surveys in California (2014-2019) have found that the pod weevil and seed beetle combined destroyed over 80% of seeds in some locations.

Herbicides that kill Scotch broom plants during the fall, winter, or early spring (before flowering), may reduce plant populations and not affect weevil abundance.

The gall mite and the seed beetle are increasing and will likely add to the level of control now provided by the pod weevil and the stem moth.

The seed beetle also attacks French broom, which currently has no insects attacking seeds, so it may provide some benefit in reducing French broom seed production.

Caveats

The pod weevil and the stem moth attack only Scotch broom and have not been found on any native species.

The gall mite and the seed beetle are not permitted, so it is not legal to move them in California.

Where Can I Get These?

The pod weevil and stem moth are widespread and likely occur wherever Scotch broom grows in California.

To date, there are no commercial sources for these insects.

Photographs

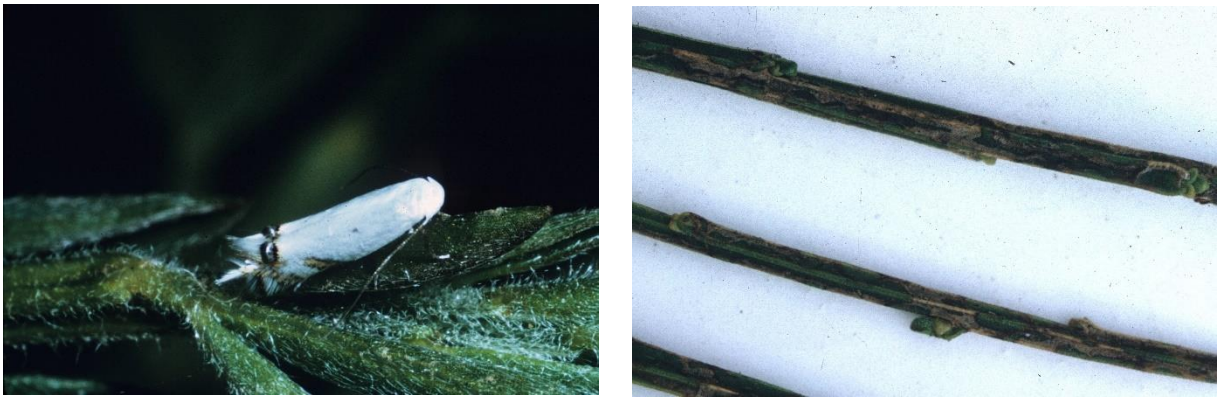

Figure 1. Scotch broom stem moth (*Leucoptera spartifoliella*) adult and larval mining damage on stems. Photo credits: USDA-ARS.

Figure 2. Scotch broom pod weevil (*Exapion fuscirostre*) adult on flower, adult feeding damage on branch, and seeds eaten by larvae. Photo credits: USDA-ARS.

Figure 3. Left: Scotch broom gall mite (*Aceria genistae*) inside opening leaf bud (20x). Photo credit: Lincoln Smith, USDA-ARS. Right: Galls on stems Photo credit: Scott Oneto, UC Regents.

Figure 4. Scotch broom seed beetle (*Bruchidius villosus*) adults (left) and seeds damaged by larvae (right). Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

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6.15 St. Johnswort (*Hypericum perforatum*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Lincoln Smith

Overview

Six species of insects that feed on St. John's wort were approved for introduction, five of which established. The leaf beetle, *Chrysolina quadrigemina* (Coleoptera: Chrysomelidae), and the root borer, *Agrilus hyperici* (Coleoptera: Buprestidae) have the most impact. The leaf beetle, *Chrysolina hyperici* (Coleoptera: Chrysomelidae), the inchworm, *Aplocera plagiata* (Lepidoptera: Geometridae), and the gall midge, *Zeuxidiplosis giardia* (Diptera: Cecidomyiidae), have little or no impact.

Two similar species of **leaf beetles**, *Chrysolina hyperici* and *C. quadrigemina,* are established in California, and the latter species (also known as the Klamathweed beetle) is the most abundant of these two species in California (Figs. 1 & 2). They have similar life cycles, but *C. quadrigemina* does better at drier sites and emerges earlier in spring than *C. hyperici*. In California, *C. hyperici* has become relatively uncommon and is found only in extreme northwest California near the border with Oregon. Both species lay eggs in the fall on the undersides of leaves. Larvae feed on the leaves and can completely defoliate plants. Pupation occurs in the ground (February to March). Adults emerge in the spring, feed on leaves and flowers for several weeks, and then hide in the soil during summer until fall rains begin.

Larvae of **the root borer** attack the roots from August to the following May or June (Fig. 3). Larval damage stunts the stems and reduces flower production, and many attacked plants die. Adult beetles are active from July to early August and can be collected by sweep net. The root borer is widespread on St. Johnswort in California, but larvae are susceptible to fungal attack at damp sites.

The inchworm is a defoliating moth that can have up to two generations per year (June to July and September to May) (Fig. 4). Defoliation weakens plants and reduces seed production. Larvae are primarily active at night and hide in the soil to pass the winter. In California, it occurs in just one location near Mt. Shasta in Siskiyou County.

The gall midge forms galls in leaf buds and has 2-3 generations per year (Fig. 5). It is rarely recovered in California, and parasites limit its ability to build up populations.

Biological control agents of St. Johnswort

Species	Common name	Distribution	Impact	Notes
Agrilus hyperici	St. Johnswort root borer	wide	high	First release in CA in 1950
Aplocera plagiata	inchworm	limited	unknown	First release in CA in 2011
Chrysolina hyperici	leaf beetle	limited	high	First release in CA in 1945
Chrysolina quadrigemina	Klamathweed beetle, leaf beetle	wide	high	First release in CA in 1946
Zeuxidiplosis giardia	gall midge	limited	low	First release in CA in 1950

How the Technique is Employed

The Kamathweed beetle quickly eliminated vast infestations of St. Johnswort in California during the late 1940s. Together with the root beetle, these two species continue to maintain the weed at low densities. It may take several years for beetles to discover new weed infestations.

Biological control agents may be present at your site. Look for signs of leaf damage by beetle larvae during late winter or by adults in the spring. If you fail to see signs of the beetles, then collect them from other sites to release. Adult Klamathweed beetles can be collected by sweep net or hand picking in May when the plant is flowering. During summer, the beetles rest in the ground and are harder to collect. Keep them cool on fresh stems with leaves and release them as soon as possible.

Collect adult root borer beetles by sweep net on hot days from July to early August.

Larval inchworms become active at night and can be collected by sweep net in midsummer or fall at, or immediately after, sunset.

Collect inchworm larvae (April, June, or September) by sweep net.

The gall midge is difficult to transfer. Infest potted plants and transplant them at the release site to allow adults to emerge from galls.

For more details, see Winston et al. (2012) listed below.

Special Tips

Focus on the agents that are known to perform well in your area (discuss with county advisors and other land managers).

The beetles perform poorly at shaded, barren, or rocky sites, whereas the defoliating moth (inchworm) does well at such sites.

While the gall midge does best at more humid sites and at higher elevations, it is rarely recovered in California.

The root borer prefers dry mountainous sites and tolerates shade better than the other species.

Caveats

The two *Chrysolina* beetles have been reported to attack the native plant *Hypericum concinnum* and the introduced ornamental *H. calycinum* but do not appear to affect their populations.

The root borer has been reported to attack a native plant, *Hypericum concinnum*.

The gall midge is able to form galls on the native plant *Hypericum concinnum*, but damage to this plant species is insignificant.

Where Can I Get These?

The two most effective agents, the Klamathweed beetle and the root beetle, are probably already at your site.

Contact your county advisor or CDFA Biological Control program.

Photographs

Figure 1. St. Johnswort leaf beetle (*Chrysolina hyperici*). Photo credit: Norman E. Rees, USDA-ARS - Retired, Bugwood.org.

Figure 2. Klamathweed beetle (*Chrysolina quadrigemina*). Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 3. Left: St. Johnswort root borer (*Agrilus hyperici*) adult. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org. Larva in root. Photo credit: Baldo Villegas, CDFA.

Figure 4. St. Johnswort inchworm (*Aplocera plagiata*). Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

Figure 5. Left: St. Johnswort gall midge (*Zeuxidiplosis giardi*) adult. Photo credit: Norman E. Rees, USDA-ARS - Retired, Bugwood.org. Right: Galls. Photo credit: Baldo Villegas, CDFA.

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6.16 Saltcedar (*Tamarix spp.*)

Lead authors: Dr. Michael J. Pitcairn, Dr. Patrick J. Moran, Dr. Lincoln Smith

Overview

One biological control agent for saltcedar has been approved by APHIS, which is a leaf beetle originally known as *Diorhabda elongata* (Coleoptera: Chrysomelidae).

Scientists collected the leaf beetle from several areas in Eurasia, looking for biotypes adapted to different latitudes and discovered that there were multiple cryptic species. The original population from northern China is now called *D. carinulata*, and one from Crete is called *D. elongata* (Fig. 1, Tracy and Robbins 2009). Two additional species (*D. carinata* and *D. sublineata*) are established east of the Rocky Mountains but are not discussed here.

Leaf beetle adults become active when green foliage appears in the spring, feeding and laying eggs on the leaves (Fig. 2, Deloach and Carruthers 2004). The larvae also feed on leaves and pupate on the soil surface and in leaf litter. The beetles can have more than one generation per year, depending on species and latitude, but adults that emerge in late summer are in reproductive diapause, and will not lay eggs until the next spring. Adults spend the winter hiding in leaf litter and soil, often near saltcedar trees. The adults are good dispersers and tend to aggregate, which causes patches of saltcedar to become completely defoliated. Trees that have access to sufficient moisture may regrow leaves later in the summer, otherwise not until next spring. Repeated defoliations can cause tree mortality.

For areas in California north of the Tehachapi Mountains, both *D. elongata* and *D. carinulata* are CDFA-approved biological control agents. Unfortunately, most of the saltcedar in central and northern California is *Tamarix parviflora*, which is not the preferred host of these *Diorhabda* beetles.

The Northern China leaf beetle (*Diorhabda carinulata*) was released in 1999-2002 in the Owens Valley area (Tinemaha Reservoir, Inyo County) on *Tamarix ramosissima* and *T. parviflora*, and this is the only area in Northern California where it has established (Pratt et al. 2019). This beetle population has persisted at extremely low densities. This beetle was also released in 2001 in Lovelock, Nevada and widely in Colorado and Utah starting in 2005, causing spectacular defoliation of saltcedar (*T. ramosissima*) (Carruthers et al. 2008, Bedford et al. 2018). The beetle has gradually moved down the Colorado River into southwestern willow flycatcher (SWFL) habitat in New Mexico, Arizona, and southern California (Dudley and Bean 2012). Defoliation of saltcedar poses a risk to SWFL, which is a federally endangered subspecies, because it nests in saltcedar in areas where willows no longer occur. Restoration of cottonwood-willow vegetation in the wake of saltcedar defoliation will be important for improving the prospects of SWFL. A lawsuit to help protect SWFL resulted in APHIS revoking the permit for *Diorhabda* beetles in 2010. Meanwhile the beetle has spread all the way down the Colorado River and is dispersing into the Mojave Desert of southeastern California. The California Department of Food and Agriculture (CDFA) does not make any releases of the leaf beetles south of the Tehachapi Mountains to avoid SWFL habitat. Biological control researchers are monitoring the beetles in southern California, but no agents can be released in this area. In 2018, *D. carinulata* was collected along the Mojave River in

San Bernardino County and released on *T. parviflora* in Butte, Kern, and Fresno Counties; however, none of the releases resulted in established populations.

The Crete leaf beetle (*Diorhabda elongata*) was released in 2003-2005 on *T. parviflora*-dominated saltcedar patches in the Cache Creek (Yolo County) and Pope Creek (Napa County) valleys, initially causing widespread defoliation (Fig. 2). The beetles are persisting and have dispersed about 9 miles/year but are not causing widespread mortality of saltcedar trees (Pratt *et al.* 2019). Initial releases of this beetle species at other sites in northern California (for example Stony Creek in Glenn County or Los Gatos Canyon in Fresno County) failed to establish. Beetles collected at Cache Creek were released in Colusa, Kern, Fresno, Napa, and Yolo counties, but all these populations also failed to establish.

Heavy feeding by the leaf beetles can completely defoliate trees in early summer, as observed at Cache Creek in 2006-2007 (Carruthers *et al.* 2008). When this happens, the beetles leave the area in search of healthy trees. They may return to defoliate regrowth later the same year or next spring, but if beetles have left the area, trees can recover from the damage. In western Colorado *D. carinulata* caused 15% to 56% tree mortality after six years (Kennard *et al.* 2016). Unfortunately, this level of impact has not been observed for *D. elongata* on *T. parviflora* in northern California (Pratt *et al.* 2019). Pheromones of the beetle have been used experimentally in traps to monitor populations and even to attract beetles to attack specific trees.

The splendid tamarisk weevil, *Coniatus splendidulus* (Coleoptera: Curculionidae), is an accidental introduction that has been found in Arizona, California, Colorado, Nevada, Oklahoma, Texas, and Utah, as well as in Mexico (Hassenflu *et al.* 2018, Silva *et al.* 2018) (Fig. 3). It is a small weevil ($^1/_8$ -inch long), and its larvae feed on the leaves of several *Tamarix* spp. Its geographic distribution and ability to cause damage to saltcedar in California are unknown.

The tamarisk leafhopper, *Opsius stactogalus* (Hemiptera: Cicadellidae) is another accidental introduction that is widespread in southern California (Fig. 4). The leafhopper has three to four generations per year, and it overwinters in the egg stage in *Tamarix* spp. shoots and woody stems. It can occur in very high numbers and result in reduced plant growth. Heavy feeding results in a yellowing of the leaves and early leaf drop, a condition called “hopper burn” (Nissen *et al.* 2009). High leafhopper populations produce large amounts of honeydew, which may attract ants that disrupt feeding by the leaf beetles but also coat leaves with a sooty mold that may increase shoot mortality (Siemion and Stevens 2015).

The splendid tamarisk weevil and tamarisk leafhopper are not permitted for use as biological control agents in California.

Biological control agents of tamarisk

Species	Common name	Distribution	Impact	Notes
Coniatus splendidulus	Splendid tamarisk weevil	Limited	unknown	Accidental introduction, found in CA in 2010. Not a permitted agent.
Diorhabda carinulata	Northern China leaf beetle	Limited	unknown	First released in CA in 2001 but failed to establish except at one site (Owens Valley, Inyo Co.); dispersing from AZ into Mojave Desert and San Bernardino Co.
Diorhabda elongata	Crete leaf beetle	Limited	moderate	First released in CA in 2003, established in only one area (Cache and Pope Creek Valleys, Yolo/Napa Co.)
Opsius stactogalus	Tamarisk leafhopper	Wide	moderate	Accidental introduction, found in US in 1907. Not a permitted agent.

How the Technique is Employed

Survey your site for the *Diorhabda* spp. leaf beetles. If they are already present, there is no benefit to releasing more, as the beetles already present will build their populations. To survey, examine saltcedar trees that show partial or complete defoliation damage (Fig. 2). Defoliation is most likely to occur between June and September. Examine stems for adult beetles (Fig. 2) and larvae. Defoliated stems will have cast larval skins and frass (feces) from larval beetles. In the absence of defoliation, sweep-net or beat a few trees (to knock insects into an open sheet or net) at your site to confirm that the beetles are absent. Note that damage from the tamarisk leafhoppers resembles beetle defoliation from a distance. Close examination of the leaves and stems will reveal the planthoppers and the yellow and possibly sooty appearance of 'hopper-burned' leaves (Fig. 4). Close examination of branches is also required to observe the splendid tamarisk weevil and/or its basket-like pupal cases.

For additional information see Nissen et al. (2009).

Special Tips

Pheromones of the beetle have been used experimentally in traps to monitor populations and even to attract beetles to attack specific trees.

Caveats

It is not permitted to release these leaf beetles in California south of the Tehachapi Mountains. Leaf beetle larvae, pupae and diapausing adults are susceptible to predation by ants. Flooding can drown insects in the ground (pupating during the summer, hibernating during the winter). The species of saltcedar that is most common in northern California (*Tamarix parviflora*) is not the most preferred or suitable species of saltcedar for the leaf beetles. The leaf beetles can attack a nontarget, non-native shade tree, athel (*T. aphylla*, Deloach et al. 2003, Moran et al. 2009), although they do not persist on it. They can also reproduce on a native plant, alkali heath (*Frankenia salina*), under confined conditions, but not when the beetles are free to disperse (Dudley and Kazmer 2005, Milbrath and DeLoach 2006, Herr et al. 2009).

Where Can I Get These?

The California Department of Food and Agriculture has a special use permit to move *Diorhabda* beetles from the Mojave River to saltcedar infestations in northern California. Unfortunately, recent efforts doing this have not been successful in obtaining sustained populations of beetles on *T. parviflora*, the predominant species in northern California. Future efforts are investigating better release methods, such as using aggregation pheromones and cages. These methods are still under development.

There are no known commercial vendors of the leaf beetles.

Redistribution of the splendid tamarisk weevil and tamarisk planthopper are not permitted in California.

Photographs

Figure 1. Crete leaf beetle *(Diorhabda elongata*) (left) and Northern China leaf beetle (*Diorhabda carinulata*) (right). Reproduced from From Tracy and Robbins (2009) with permission from copyright holder.

Figure 2. Top left: Saltcedar (*Tamarisk ramosissima*) defoliated by *Diorhabda* leaf beetles in background. Photo credit: Dan Bean, Colorado Department of Agriculture. Top right: Saltcedar leaf beetle adult. Photo credit: Bob Richard, USDA APHIS PPQ, Bugwood.org. Middle right: Saltcedar leaf beetle larva. Photo credit: Eric Coombs, ODA, Bugwood.org. Bottom: Heavy infestation of larvae. Photo credit: Michael J. Pitcairn, CDFA.

Figure. 3. Splendid tamarisk weevil *(Coniatus splendidulus*) adult. Photo credit: Zeynep Ozsoy, Colorado Mesa University.

Figure. 4. Tamarisk leafhopper (*Opsius stactogalus*). Photo credit: Whitney Cranshaw, Colorado State University, Bugwood.org.

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6.17 Tansy Ragwort (*Senecio jacobeae*)

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Overview

Three species of insects have been introduced as biological control agents of tansy ragwort in California: a flea beetle (*Longitarsus jacobaeae*, Coleoptera: Chrysomelid), the cinnabar moth (*Tyria jacobaeae*, Lepidoptera: Erebidae) and the ragwort seed head fly (*Botanophila seneciella*, Diptera: Anthomyiidae). The flea beetle has the most impact on reducing abundance of the weed, but the cinnabar moth provides some additional control. The seed head fly has not established in California.

The flea beetle and moth have been highly effective at reducing tansy ragwort populations in California and Oregon, reducing it by up to 99% in ungrazed areas. The estimated benefit-to-cost ratio of this project in Oregon is about 14:1, with annual benefits of $5 million per year (in 1993). Biological control alone does not provide control of tansy ragwort in grazed pastures. Experiments have shown that both the insects and plant competition contribute to reduction of tansy ragwort. Both insects are good dispersers. Disturbances that cause seed in the soil seed bank to germinate lead to temporary resurgence of the weed, which is then controlled by insects in 1 to 3 years.

The flea beetle has one generation per year (Fig. 1). Adults feed on foliage creating small shot holes, and lay eggs around the bases of rosettes. Larvae feed inside leaf petioles and the root crowns causing extensive damage and sometimes plant death. Three flea beetle biotypes have been introduced that differ in their biology. The Italian CPNW biotype (= Coastal Pacific Northwest) is adapted to regions with mild winters and dry summers. Adults aestivate during the summer and begin feeding and laying eggs in the fall after precipitation begins. Eggs can be laid throughout the winter, and larvae continue developing until spring. Pupation occurs in the soil, and adults emerge in the spring and feed briefly before aestivating during summer. The Italian CAD biotype (=cold adapted) is adapted to regions with colder temperatures and humid summers. Larvae continue feeding into the summer, pupation occurs in midsummer, and adults emerge in late summer. The Swiss biotype is adapted to regions with even colder winters and humid summers. Adults lay eggs in summer and fall, but eggs do not hatch until the spring. Larvae develop in spring, pupate in early summer, and adults emerge in summer. All the biotypes appear to perform best in dense infestations at sunny sites that are not seasonally flooded. The Italian CPNW biotype has been very successful in California, whereas the Italian CAD biotype has done better in the Cascade Mountains and Intermountain West up to about 1,300 ft elevation. The Swiss biotype does well at higher elevations, up to about 5,500 ft. No non-target plant effects have been reported for any of these biotypes.

The cinnabar moth has one generation per year (Fig. 2). Adults lay clusters of eggs on the underside of leaves. The orange-and-black-banded larvae are conspicuous and feed on the leaves and shoots in spring and summer. Pupation occurs in the soil, and adults emerge the following spring. Although larvae can completely defoliate plants, they are often able to leaf out again later in the year after the onset of fall precipitation. Insect predators, parasites, and a microsporidian disease can limit the effectiveness of the moth. In Oregon, the cinnabar moth has been reported to develop on some native non-target

plants, including *Senecio triangularis* and *Packera pseudaurea*. Non-target use of these plants in California has not been observed.

Biological control agents of tansy ragwort

Species	Common name	Distribution	Impact	Notes
Botanophila seneciella (=*B. jacobaeae*)	ragwort seed head fly	failed to establish	unknown	first released in CA in 1966
Tyria jacobaeae	cinnabar moth	wide	high	first released in CA in 1959
Longitarsus jacobaeae (=*L. flavicornis*)	tansy ragwort flea beetle	wide	high	first released in CA in 1969

How the Technique is Employed

If biological control agents are already present at your site, there is no need to release more. Look for signs of insects and their damage. During summer, look for orange-and-black-banded caterpillars and/or defoliation caused by the cinnabar moth. Adult moths have a conspicuous red and brown wing pattern. In the fall or spring, look for shot holes in leaves caused by adults of the flea beetle, or split open rosettes to look for root crown damage.

Cinnabar moth larvae can be collected in the summer by tapping plants to make larvae fall into an open container. Larvae that have pinkish-colored feces are probably infected by a *Nosema* pathogen and should not be collected for redistribution.

Collect adult flea beetles by sweep net or insect vacuum (D-Vac), in the fall for the Italian CPNW biotype or summer for the others. Look for rosettes that have shot holes in the leaves.

For additional details see Winston et al (2011).

Special Tips

Knowing what insects are present may help you to integrate other management strategies. The flea beetle larvae feed in the fall to early spring in California whereas the moth caterpillars feed during summer.

The flea beetles oversummer in sheltered places, such as in tree bark, under rocks in leaf litter and even in house attics.

Biological control of tansy ragwort has been most successful in ungrazed areas.

Caveats

Mowing during summer will probably kill the cinnabar moth caterpillars and deprive them of foliage to eat.

Herbicides that kill tansy ragwort will deprive the insects of the ability to reproduce. However, the insects will search for the remaining plants that have not been killed. Thus, biological control can be complementary to herbicide or other control treatments, especially if there are areas that escape the treatment (too difficult to access or too environmentally sensitive to treat).

In Oregon, the cinnabar moth has been reported to develop on some native non-target plants, including *Senecio triangularis* and *Packera pseudaurea*. Non-target use of these plants in California has not been observed so there are no restrictions on its use in California.

No non-target plant effects have been reported for the flea beetle. A similar flea beetle, *Longitarsus ganglbaueri*, occurs on tansy ragwort in California, Oregon, and Washington, and is an accidentally introduced non-native species that feeds on some native plants, including *Packera pseudaurea*.

Where Can I Get These?

Collect adult flea beetles by sweep net or insect vacuum in the fall. Look for rosettes that have shot holes in the leaves.

The flea beetle and cinnabar moth may be available from your county Agricultural Commissioner.

Photographs

Figure 1. Adult tansy ragwort flea beetle (*Longitarsus jacobaeae*). Photo credit: Laura Parsons, University of Idaho, PSES, Bugwood.org.

Figure 2. Left: Cinnabar moth (*Tyria jacobaeae*) adult. Photo credit: Mark Schwarzlander, University of Idaho, Bugwood.org. Right: Cinnabar moth larva. Photo credit: Leslie J. Mehrhoff, University of Connecticut, Bugwood.org.

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6.18 Yellow Starthistle (*Centaurea solstitialis*)

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Overview

Six species of insects and one rust fungus that attack yellow starthistle (YST) have become established in California. All the insects attack the flower heads, which reduces seed production. The hairy weevil and the false peacock fly have achieved high densities over large areas in California. The latter species was unintentionally introduced, and is not permitted for release; however, it is very specific to yellow starthistle (Balciunas and Villegas 2007). Currently, the combination of these two insects provides the most impact.

Yellow starthistle populations have decreased in some areas, especially in ungrazed grasslands that have a dense cover of grasses. In a long-term field study by CDFA, the hairy weevil attacked 20-80% of flower heads (variation year-to-year), the false peacock fly 2-28%, the gall fly 1-23%, the flower weevil 0-1%, and the bud weevil 0-4% (Pitcairn *et al.* 2005). Some naturally occurring generalist microbial pathogens (*Ascophyta* n. sp., *Sclerotinia minor* and *Colletotrichum gloeosporioides*) attack seedlings, which can cause up to 90% mortality (Pitcairn *et al.* 1999). The introduced rust (*Puccinia jaceae* var. *solstitialis*) was distributed widely throughout California but did not establish well at most sites and generally appears to be ineffective in California (Woods *et al.* 2010). The insect biological control agents feed directly on seeds in flower heads and reduce seed production, but they do little to reduce the growth or size of existing plants. To achieve population-level effects on yellow starthistle, high levels of seed destruction (e.g., >80 may be necessary. The rosette weevil, *Ceratapion basicorne*, was permitted for release in 2019 and was first released in April 2020 in Solano County. However, because of its slow rate of population growth and difficulty to rear in the laboratory, it will take several years before it is available for general distribution. This insect should help to reduce plant size and survivorship.

The bud weevil, *Bangasternus orientalis* (Coleoptera: Curculionidae), lays an egg, which looks like a black lump on the stem or leaf just below a flower head (Fig. 1). The larva tunnels up the stem into the flower head and consumes the developing seeds. A pupal chamber is formed inside the flower head, and adults emerge by the end of the summer leaving a characteristic “bullet hole” and hide during winter hibernation.

The rosette weevil, *Ceratapion basicorne* (Coleoptera: Curculionidae), was permitted in 2019 for release in California. It has one generation per year. Adults start to feed on rosette leaves in spring, and lay eggs in the leaf blades and midribs (Fig. 2). Larvae tunnel down the petiole and feed inside the upper root. More than one insect can develop inside a plant. Pupation occurs inside the plant, and adults emerge at the time the plant is bolting (late May to June). Adults feed and mate on the plant for a week or two then disappear until the next spring.

The peacock fly, *Chaetorellia australis* (Diptera: Tephritidae), lays one or more eggs in a flower bud (Fig. 3). Larvae chew on developing seeds, which leaves a mixture of seeds and loose debris inside attacked flower heads. This fly has a characteristic papery 'puparium' in which it completes development to the adult stage inside the flowerhead. More than one insect can develop inside a flower head. There are two

or more generations per year, and the insect passes winter as a larva inside the seed head. This species emerges earlier in the spring than *C. succinea* and depends primarily on bachelor's button (*Centaurea cyanus*) as a host for its first generation. Because bachelor's button is not very common in California this species is rare.

The false peacock fly, *Chaetorellia succinea* (Diptera: Tephritidae), is very similar to the peacock fly but has an extra spot on its thorax (Fig. 3). This is the most widespread of the YST insects in California and often is seen resting on a flower bud. Its biology is very similar to that of *C. australis*, and it was mistakenly introduced for this species in 1991. Since then, its host specificity has been studied, and it appears to not pose a risk to any nontarget native plants in California. This insect has been found to attack one variety of safflower where it was being grown to foster game birds, but it was not found in fields for commercial production (Balciunas and Villegas. 2001, 2007).

The hairy weevil, *Eustenopus villosus* (Coleoptera: Curculionidae), is the most effective permitted biological control agent for yellow starthistle (Fig. 4). Adults feed on the first small flower buds, which can change the architecture of the plant (Fig. 5). Flower buds normally develop at the tips of branches, but the weevil eats many of these, which causes secondary buds to develop further down the branches. When flower buds get larger, the weevil chews a small hole in the side, where it lays an egg and covers it with black frass. These oviposition sites can be readily seen on yellow starthistle flower heads when the hairy weevil is present. One larva develops inside the flower head and consumes most of the developing seed. It pupates inside the flower head, and adults emerge by the end of the summer to hibernate off the plant.

The flower weevil, *Larinus curtus* (Coleoptera: Curculionidae), is often seen on an open flower, with its head buried deep among the florets (Fig. 6). It lays an egg in the open flower head, and the larva consumes developing seeds. It pupates inside the flower head, and adults emerge by the end of the summer to hibernate off the plant.

The gall fly, *Urophora sirunaseva* (Diptera: Tephritidae), creates a hard nut-like gall from the flower ovary, inside of which its larva develops (Fig. 7). Adults have clear wings with a black 'UV' pattern on the wings. The flies can have more than one generation during the summer, and they spend the winter as mature larvae inside the flower head.

The yellow starthistle rust, *Puccinia jacea* var. *solstitialis* (Uredinales: Pucciniaceae), has a complicated life cycle with five life stages (Fig. 8). It is known to infect only yellow starthistle, bachelor's button (*Centaurea cyanus*) and to a very limited extent safflower (Bruckart 2006). The rust produces resting spores (teliospores) that resist cold temperatures during winter. Resting spores germinate in the spring and produce a sequence of different kinds of spores that infect plants. The final type of spores (urediniospores) is able to reinfect plants during the growing season. Optimal conditions for infection are cool (65-70°F) and humid (at least 8 hours of dew). Infected plants produce pustules in 2 or more weeks, depending on temperature, which release spores that disperse in the wind. In the summer, resting spores are produced, which are crucial for initiating infections in the following spring. The rust was released at 176 sites in 40 counties during 2004-2006, but it persisted at only one site close to San Francisco Bay in Sonoma County.

Biological control agents of yellow starthistle

Species	Common name	Distribution	Impact	Notes
Bangasternus orientalis	bud weevil	wide	low	First released in 1985, more abundant in Coastal Mtns in northwest CA
Ceratapion basicorne	rosette weevil	new	unknown	First release in April 2020 in Solano Co.
Chaetorellia australis	peacock fly	wide	low	First released in 1988, more common on bachelor's button than YST
Chaetorellia succinea	false peacock fly	wide	moderate	Accidental introduction in 1991. **Not** a permitted agent. The most abundant & widespread species.
Eustenopus villosus	hairy weevil	wide	moderate	First released in 1990, more abundant in northern CA, Sierra Foothills & Coastal Mtns
Larinus curtus	flower weevil	wide	unknown	First released in 1992
Puccinia jacea var. solstitialis	yellow starthistle rust	limited	low	First released in 2003; almost no establishment.
Urophora sirunaseva	gall fly	wide	low	First released in 1984; more abundant in the coastal mountains

How the Technique is Employed

Look for presence of insects and their damage to determine what species are present at your site. It is not worth releasing insects if they are already present. Before flowers bloom, the hairy weevil feeds on small flower buds, causing them to 'flag' (Fig. 5). This damage also changes the plant's architecture, as secondary buds develop into flowers. The presence of seed head insects can be detected by opening mature flower heads and looking for larvae and/or signs of damage (Figs. 1, 3, 4, 6, and 7).

Collect adult insects in the field by sweep net, although this is difficult once the spines appear on the flower heads.

Detailed information and photographs can be found in DiTomaso *et al.* (2006) and Randall *et al.* (2017).

Special Tips

It is not known where the weevils overwinter, but it is likely in sheltered places, such as in tree bark, under rocks or in leaf litter. The fly species overwinter inside flower heads as mature larvae and may be susceptible to predation by rodents or grazing ungulates eating flower heads.

Some of these agents, particularly the hairy weevil and the false peacock fly, also attack tocalote or Maltese starthistle (*C. melitensis*) and Sicilian starthistle (*C. sulphurea*).

Caveats

Knowing what insects are present may help you to integrate other management strategies. The three weevil species emerge from the flower heads in the summer and overwinter as adults away from the plant. The fly species overwinter inside flower heads as larvae. Thus, for example, fall grazing of flower heads by goats would kill most of the flies, but not affect the weevils.

Mowing yellow starthistle in the spring will delay flowering, which may reduce the effectiveness of the insects, who will grow old before they can lay eggs.

Herbicides that kill yellow starthistle before it produces mature flower heads will deprive seed head insects of the ability to reproduce. However, the adults will search for the remaining plants that have not been killed. Thus, biological control can be complementary to herbicide or other control treatments, especially if there are areas that are not treated (e.g., too difficult to access or too environmentally sensitive to treat).

The false peacock fly is not a permitted agent and should not be redistributed. It is known to attack two native species of basket flower, neither of which occur in California.

There are no reports of non-target use by the permitted biocontrol agents.

Where Can I Get These?

Some insects may be available from your county Agricultural Commissioner. Historically, some insects have been commercially available by some vendors such as Biological Control of Weeds, Inc. (www.bio-control.com).

Photographs

Figure 1. Yellow starthistle bud weevil (*Bangasternus orientalis*) adult, eggs and exit hole in flower head. Photo credit: USDA-ARS.

Figure 2. Yellow starthistle rosette weevil (*Ceratapion basicorne*), adult nearing feeding hole on leaf and larval damage to root crown. Photo credit: USDA-ARS.

Figure 3. False peacock fly (left, extra spot) and peacock fly (right), and hibernating larva inside mature flower head; note chewed plant debris. Photo credit: USDA-ARS.

Figure 4. Hairy weevil (*Eustenopus villosus*) adult. Photo credit: Charles Turner, USDA-ARS, Bugwood.org. Center: Egg hole and post-bloom signs of infestation Photo credit: Baldo Villegas, CDFA. Right: Pupa inside cut open pupal chamber. Photo credit: USDA-ARS.

Figure 5. Buds killed by hairy weevil (pink arrows) are replaced by secondary buds (blue arrows). Normal plant growth (right) with flower buds at branch tips. Photo credit: CDFA.

Figure 6. Left: Yellow starthistle flower weevil (*Larinus curtus*) adult. Photo credit: Baldo Villegas, CDFA. Larva inside the flower head. Photo credit: Charles Turner, USDA-ARS, Bugwood.org.

Figure 7. Adult yellow starthistle gall fly (*Urophora sirunaseva*) and larva inside a dissected gall in the flower head. Photo credit: USDA-ARS.

Figure 8. Yellow starthistle rust (*Puccinia jacea var. solstitialis*) pustules on leaves. Photo credit: Eric Coombs, Oregon Department of Agriculture, Bugwood.org.

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