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Herbicidal Weed Control Methods for Pastures and Natural Areas of Hawaii

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Table of Contents

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The severity of the impact of weeds on ranching and forest management is often underestimated. Besides competing with forage plants for soil nutrients, sunlight, and water, and thereby suppressing forage growth, weeds also create management problems.

For example, brush in Texas used up over two times the water requirements of all the cities and industries in that state in 1980[32]. Many weeds are poisonous, or armed with spines that may injure animals directly or by leading to infections. Mesquite (*Prosopis* spp.) infestations in Arizona suppressed forage growth and promoted soil erosion and rain runoff[66]. On brush-infested ranches, cattle are more skittish, requiring more labor to manage; more bulls are required to service the herd; newborn calves instinctively remain in hiding as mowers approach and may be killed. Another Texas study indicated that brush-free ranches could stock 42 percent more animals and would need 59 percent less permanent labor and 58 percent less labor at roundup[34]. Weeds also threaten native plant communities in forests and shrublands and, thereby, the native animals dependent on the specific native plants or complex of plants that make up that plant community. The original ecosystem is thus replaced by a new, exotic one[10].

Weeds are often more competitive than native plants because of a lack of natural controls such as diseases and predators. Many are able to suppress plants growing close to them by producing growth retardants. Indirectly, they suppress natives by supporting wildfires, which may be devastating to native plants but which may be natural to alien species; they may fix nitrogen, which alien species may be better able to utilize than natives[102]. The ecology of natural areas worldwide is threatened by invasive weeds. Thus weed management is an on-going problem for ranchers, foresters, and other land managers.

Use of herbicides is an effective and efficient means of managing weeds. Contrary to popular perception, it is also very safe. In many cases there are no practical alternatives to chemical weed control methods. However, herbicides can easily be misused and inflict unintended injury to non-target organisms. In order to ensure efficacy, efficiency, and economy—and non-target safety—users of herbicides must have an understanding of herbicide application principles and plant responses to herbicides.

Methods of weed control

Prehistoric humans saw the need to deal with weeds. Nearly 3000 years ago, people in Europe cleared trees and brush from around oak and nut trees to increase the size and number of acorns and nuts[21]. Throughout history, many methods of control have been devised, all of which are still used today. While this publication deals with chemical methods of weed management, one or more of the other methods are often used in conjunction with chemical methods. Several of these methods require the authority and resources of the government (e.g., quarantine and biocontrol). Others are in the hands of the herbicide user (e.g., mechanical methods). Because an understanding of the other methods can be helpful in developing comprehensive weed management strategies, they are briefly described in the following paragraphs.

Quarantine and sanitation

The most economical method of weed control is prevention. Weed species are prevented from moving into uncontaminated areas by quarantine, the official regulation of weed movement across political borders, and by sanitation, the unofficial control of weed movement (e.g., cleaning shoes and clothing between hikes and corraling livestock for a time between infested pastures and uninfested pastures). Unfortunately, with increasing worldwide commerce, preventing weed movement is becoming more difficult. New weeds and other pests do get by quarantine, either deliberately or inadvertently.

One of the problems is that weediness is unpredictable. A noxious weed in one area can be benign in another. A further difficulty is that many alien plant introductions may be benign for years or decades before suddenly exploding into a serious weed pest(17). There are ongoing attempts to characterize weediness so that quarantine can be made more effective and efficient. It has been suggested that some of the characteristics that determine weediness include short cycles between seedings, production of many seeds, small seeds, seed dispersal by vertebrates, adaptation to a large latitudinal range, and absence of the alien genus in the invaded area. The USA and most of the world maintain "dirty lists" of prohibited plants. Australia and New Zealand maintain a "clean list" of plants that are allowed to be imported; everything not on the list is prohibited(17). These two countries require a strict protocol for importing prohibited plants for research and possible development into commercial crops. In either approach, knowledge of what makes a plant a weed helps in formulating quarantine lists(17). Every noxious weed kept out of Hawaii means economic losses and environmental damage avoided and a great deal of money and effort *not* required to deal with that weed.

Biocontrol

Weed biocontrol is the suppression of weeds by insects and microorganisms that feed on the target plants or otherwise parasitize them. Hawaii has been a pioneer in classical biocontrol of weeds; i.e., biocontrol in which the biocontrol agent is able to sustain itself after release into the environment. The Board of Agriculture and Forestry began biocontrol work in the early 1900s. Early successes against lantana and prickly pear cactus and more recent success with Hamakua pamakani and Maui pamakani resulted from these efforts(38) (see Appendix II for botanical names of weeds of Hawaii). While successful biocontrol is extremely economical, success is not assured. Efforts on gorse, faya tree, christmasberry, and others have not been fruitful so far. Furthermore, success may not be complete. Lantana is still a serious problem over large areas. In addition, because biocontrol is species-specific and there are a couple of hundred serious weed species and only limited resources to do the exploratory, safety, and efficacy research, biocontrol has to focus on only a few of the most serious weeds. Recently there has been interest in mycoherbicides, pathogenic fungi that are sprayed onto weeds, but in contrast to classical biocontrol, these fungi are unable to persist in the environment and die out with the weed.

Cultural control

Cultural control includes those management practices that modify the agroecosystem to make the pasture, crop, or forest ecosystem resistant to weed establishment and, at the same time, support overall economic goals. Examples include fertilizing pastures to provide not only greater yields but also quicker and denser ground cover; managing livestock using intensive grazing management systems(101) in which pastures are intensively grazed for short periods, allowing grazing to refresh the forage and trampling to suppress the weeds, followed by a longer rest period for grass recovery; and integrating sheep or goats to browse brush species and fowl to graze herbs and grasses(90). Some reasonably call the use of livestock in weed management biocontrol, but the difference is that livestock husbandry is a form of production agriculture, whereas the use of invertebrates or microbes is a specific weed management tactic.

Mechanical or manual control

Prior to the development of modern herbicides, ranch and forest managers relied mainly on mechanical methods of weed control, such as grubbing, bulldozing, dragging, cabling, and mowing. Ranchers used to pull weeds out of the ground with tractors or grub them out with hand tools. These methods were expensive, injurious to forage species, and ineffective over the long term. Heavy equipment exposed the soil to erosion and brought large rocks to the surface, which thereafter hindered mobility of horses and equipment. Another serious drawback of mechanical methods of weed control was that they were labor-intensive and therefore slow. Ranchers did not have enough slack periods to divert sufficient manpower to control all the weeds on the ranch in a timely manner. The demands of other tasks, equipment breakdowns, rains, and soggy grounds often precluded operations on parts of the ranch. Steep terrain or rocky ground also hindered weed control operations. Weed control deferred resulted in a more difficult task later.

The most serious aspect of mechanical control is its hazards. Agriculture is a very dangerous occupation, recording 50 deaths per 100,000 workers per year against 11 per 100,000 per year for all industries combined(70). In 1993, there were 130,000 agricultural work-related injuries and 1100 deaths[27]. Tractor rollovers are especially dangerous, accounting for 15–25 percent of farm deaths. Although the data do not so specify, some of these accidents and deaths undoubtedly occurred during weed control operations. Because mechanical control suppresses weed growth only for short periods, frequent retreatments are required, increasing worker contact with dangerous equipment.

Weeds germinate from an inexhaustible seed supply in the soil, or they resprout from stumps, roots, or stem fragments. In high-rainfall areas, new flushes from cut stumps of some species can grow 3–4 ft tall in 3 months. Mechanical methods are often used in pastures and forests, primarily where the weeds, especially woody or other large plants, must be cleared immediately either for aesthetics or safety, or as a pretreatment to herbicide applications.

Herbicides

Compared to mechanical weed control methods, herbicides provide greater efficacy at lower cost. Properly managed, herbicides provide relatively long term weed control. Spraying equipment is generally cheaper to purchase and operate than the heavy equipment used in mechanical weed control. Chemical weed control is much more rapid and provides longer term weed suppression than mechanical methods. Furthermore, herbicidal weed control results in greater grass production in pastures than does clipping of weeds[18]. Chemical methods reduce labor costs, provide greater flexibility in the management of labor and, most importantly, reduce the risk of accidents by reducing fatigue and worker exposure to power equipment and sharp implements.

For large tracts of land, aerial applications can be extremely cost-efficient, with costs per unit area as much as a tenth the cost of ground applications. Aerial applications can cover hundreds of acres per day, versus 5–75 acres per day with ground equipment. Moreover, aerial applications can be made on rough terrain and soggy soils where ground rigs cannot operate.

It is commonly perceived that a single herbicide application can solve any weed problem and that herbicides are extremely toxic. Neither is true. Properly used, herbicides can reduce weed populations quickly and selectively, and thereby provide immediate increases in grass production in pastures or native plant growth in forests. However, even under the best of circumstances, herbicides will not eradicate widely established weeds. Herbicides offer suppression of weed populations quickly and for longer periods than mechanical control methods.

However, herbicides alone are not the answer to weed problems. Indeed, effective weed management can seldom be achieved by a single method or action. Herbicides provide a means to suppress or even eliminate standing weeds. However, it cannot prevent re-infestation except by repeated application, unless management practices (e.g., fertilizer application, grazing) or ecological conditions are changed (e.g., biological control, establishment of a canopy of desirable plants, exclusion of ungulates) to exert more pressure on the weed population. Herbicides are a management tool, effective and safe if used properly.

Herbicide hazards in perspective

There is a great deal of concern about the health hazards of pesticides, including herbicides, that is a source of needless anxiety. To be sure, some pesticides are extremely toxic (acute toxicity) and do require commensurately extreme precautions in their handling and management, as is required with any toxic substance. Fortunately, most herbicides are not highly toxic, and most serious cases of poisoning have been the result of the victims swallowing one of the more toxic chemicals rather than from unavoidable exposure during normal use or through consumption of foods derived from treated crops. As in all occupations, constant education and training are required to reduce exposure to hazards and to deal with emergencies.

Perhaps the greater perceived threat in the public mind is that pesticide residues in food, air, and water increase the risk of diseases, especially cancer (chronic toxicity). The source of this concern, however, is animal tests in which massive doses are administered to susceptible animals. Using assumptions that greatly exaggerate human susceptibility and exposure to pesticides, these data are then converted to lifetime risks to humans. These assessments are often misunderstood as representing predictions or even realized casualties. Confusion is compounded by the language of risk assessment, in which risks are expressed as numbers of human illnesses pesticides will supposedly cause.

Toxicologists are almost unanimous in the view that animal tests are inappropriate for determining actual risks to humans[2, 4, 85, 99, 116]. After 60 years of pesticide use, during the first decades of which regulations were not as stringent as they currently are, age-adjusted cancer rates have not changed, except for lung cancer, which has soared, and stomach cancer, which has declined[29]. Research[30] reviewing human epidemiological studies has concluded that pesticides are "unimportant" as a cause of cancer; that the real causes of cancer were more a matter of lifestyle (diet, smoking, exposure to sunlight) than environmental pollutants.

In the USA the average life span, an indicator of public health, has been steadily increasing in the face of widespread pesticide use, to the point that the average now approaches the maximum human life span. Furthermore, dozens of naturally occurring chemicals in foods (e.g., vitamin A), including fruits and vegetables, were carcinogenic in laboratory tests, and these added up to 10,000 times the amount of pesticides residues in foods[4, 104]. Even that may be underestimated by a factor of 10[105]. At current levels of synthetic chemical residues, one would consume only 0.1 oz of synthetic chemical residues from foods in an 80-year lifetime[3, 37] and another 0.1 oz from drinking water[9]. Not all of these residues would be pesticides or laboratory carcinogens. In the same lifetime, one would consume 97 lb of natural carcinogens. Evidence also indicates that fruits and vegetables in diets, despite their natural carcinogenic components, actually prevent cancer[30] because they also contain high levels of anticarcinogens[2]. Thus pesticide misinformation and scares cause more harm than good if they cause people to avoid fruits and vegetables for fear of the pesticide residues they may contain. Rather than poisoning our food, pesticides have helped to provide the most bountiful and wholesome food supply in history. In light of the available evidence, the prudent course recommended by health scientists is not to disavow use of pesticides but to use them appropriately.

Methods of herbicide application

To attain the most economical and effective chemical weed control with minimal untoward environmental effects, herbicides must be properly managed, not applied haphazardly to the weeds. Based on the weeds to be controlled and the particular situation at hand, the user must determine the method of application, the herbicide, rate, and time of application. There are several methods of herbicide application, each with its own particular advantages and utility.

Conventional foliar methods

The most common herbicide application method is foliar application by spraying (Figure 1). It is the easiest and most economical method of applying herbicides. Herbicides can be applied with knapsack sprayers, power equipment, or by aircraft. In addition, recent innovations have made possible very-low-volume and ultra-low-volume applications and wipe-on systems.

Choice of herbicide

The user should choose, from among the herbicides registered for the intended use, the herbicide best suited to the particular goals of efficacy, economy, and environmental protection. Obviously, the herbicide must be effective on the target weeds. Certain weeds are more sensitive to one herbicide than to another or even to another formulation of the same herbicide. For example, 2,4-D

Figure 1. Foliar application of herbicide. Coverage of the entire canopy, not drenching, is critical.

is effective on many herbaceous broadleaves but is weak on most woody plants. Legumes (Fabaceae) such as catsclaw and hilahila and composites (Asteraceae) such as tropic ageratum and ragweed parthenium are generally very susceptible to picloram, triclopyr, and clopyralid, while the mustards (Brassicaceae) are tolerant of these herbicides. The polygonaceous weeds (spiney emex, kamole) are extremely sensitive to dicamba. Most broadleaves are more sensitive to 2,4-D ester than to the amine salt formulation.

Typically, a given weed species will be susceptible to more than one herbicide. Other things being equal, the lower-cost herbicide should be used. However, in determining the cost, the cost per acre, and not the cost per gallon, should be considered. For example, catsclaw can be controlled with 0.2 lb picloram active/acre. Therefore, one gallon of picloram (2 lb/gal) is sufficient to treat 10 acres of catsclaw. Even though picloram may cost $100 per gallon, it would be cheaper than a herbicide costing $50 per gallon that can treat only 2 acres of catsclaw ($10/acre vs. $25/acre).

Other considerations also affect the choice of herbicide. Continued use of a single herbicide over time can result in shifts of weed populations toward species that are naturally tolerant of that herbicide. Also, weed species initially susceptible to a herbicide may develop resistance to that herbicide if it is used repeatedly over time. Resistance usually takes many years to develop, but sulfonylureas (e.g., metsulfuron) and imidazolinones (e.g., imazapyr) have triggered resistance in certain weeds in as few as four years. Over-reliance on any herbicide in these two families will result in resistance to all herbicides in both families[52, 65, 92]. Rotation of methods of weed control and herbicides will help to prevent weed population shifts and buildup of resistance.

To prevent contamination of groundwater and surface water bodies, the applicator should avoid or reduce the use of persistent, soil-mobile herbicides in high-rainfall areas.

Herbicide selectivity

Herbicides are "selective" if they kill or injure certain plants but not others, e.g., dicots (broadleaf plants) but not monocots (such as grasses). Herbicides are "nonselective" if they kill or injure all plants to which they are applied. Selectivity allows the convenience of broadcast applications. However, herbicides effective against broadleaf weeds also kill desirable legumes. Heavy grazing to defoliate forage legumes before spraying, or using a different formulation (e.g., 2,4-D amine instead of ester), may allow the legumes to escape serious injury. Spot spraying or other directed application procedures may also protect forage legumes. There are a number of grasskillers (e.g., fluazifop) that can be used where dicots need to be protected.

Herbicide persistence

Herbicides that are readily detoxified in the soil are "nonpersistent" and those that resist breakdown are "persistent." Persistent herbicides provide long-term weed control. However, if legumes in pastures or natives plants in forests are to be planted into an area after herbicide treatment, persistent herbicides may injure seedlings of such plants. Thus the choice of a herbicide may depend on the need for longer-term suppression on the one hand and the residual toxicity to desirable plants on the other.

Herbicide formulations

Some herbicides are available in hydrophilic (water loving or water soluble) or lipophilic (oil loving or oil soluble) formulations; 2,4-D and triclopyr are available in both types of formulation. Commonly, the hydrophilic formulations are amine salts and the lipophilic formulations are emulsifiable esters. Both types of formulation may be applied with water. The amine salts form true solutions with water, and the esters form an emulsion. The solution is clear, the emulsion is milky. The emulsion, micro-droplets of oily substance suspended in water, must be agitated occasionally to keep the herbicide formulation and water from separating in the tank. In general, esters are more effective than salts because the oily nature of esters allows them to adhere to and penetrate the waxy cuticle of leaves better than salts. Esters therefore are better in situations where rain is likely to occur shortly after the herbicide application, because they enter the plant quickly and resist being washed off the leaves by rain.

Esters are more volatile than amine formulations. Esters can volatilize from the spray droplets and from the plant and soil surfaces. The volatilized herbicide can then be carried with air movement to injure sensitive crops and other nontarget plants downwind. This is called "vapor drift," in contrast to "spray drift," which is the movement of the spray droplets or solid particles. Modern ester formulations are "low volatile" but may still drift if improperly managed (e.g., applied with a mist blower). Where wind direction is unfavorable, temperature is likely to be high, and sensitive plants are near, it would be safer to use a non-volatile product. Volatilization of esters can also reduce herbicide efficacy on hot days by reducing the effective rate[22, 100]. For basal bark applications (to be discussed later), oil-soluble formulations are essential to the efficacy of the method.

Surfactants

Surfactants, a coined term for "surface-active agents," are chemicals that change the physical properties of liquid surfaces. Surfactants, depending on the chemical or blend of chemicals used, can act to enhance emulsification, dispersal, wetting, spreading, sticking, and leaf-penetration of the solution(8). Although soap and household detergents are surfactants, they are not very effective as agricultural surfactants and should not be used for that purpose. Surfactants aid the performance of herbicides by

- improving wetting of the weed; "wetting agents" or "spreaders" enhance the spread of the spray droplets and increase the area of contact between the droplets and the leaf surface and, therefore, penetration of the leaf surface
- increasing resistance of the spray deposit to washing by rain (stickers); the longer the contact between the herbicide and the plant surface, the greater the amount of herbicide absorbed
- reducing the rate of drying of the spray deposit (humectants); dry herbicides will not penetrate the leaf surface
- reducing the proportion of very fine droplets, thus reducing spray drift (drift retardants or thickeners)
- allowing the suspension of insoluble pesticides, i.e., wettable powders, in water (emulsifiers).

Although reduction of surface tension of the spray droplets is very important in increasing the efficacy of herbicides, it is not the only means by which surfactants work(97). Efficacy increases at surfactant concentrations beyond that which provides minimum surface tension(55), suggesting other mechanisms are at work. Surfactants may not be necessary when the plant is succulent, but they can help with mature plants with hardened cuticles(59). The effects of surfactants vary. They generally increase uptake of herbicides and may increase tranlsocation but may sometimes decrease translocation by causing too severe injury to the target plant(15, 35, 84).

Rates of application

Herbicide users should apply the recommended rate. Herbicide labels usually state the recommended rate in terms of both amount of product and of "active ingredient (a.i.)" or "acid equivalent (a.e.)" per acre. "Acid equivalent" is preferred for herbicides that are acids in the parent form. "Active" is used in this publication to cover either of these terms, whichever is appropriate. Overdosing is a common error as appliers, trying to get "better" or "quicker" or "once and for all" kill, may increase the herbicide concentration or the spray volume rate, or both. The result is unnecessary expense, unnecessary release of herbicide into the environment, and, ironically, poor weed control.

Effective weed kill with systemic foliar herbicides depends on the herbicide being translocated from the leaves via the phloem into the stem and roots. Too high a rate will shut down the phloem too soon, before the herbicide can be translocated to sites of action(39, 51, 60, 62, 89). Even though treated woody plants might be quickly and completely defoliated, they would recover quickly(12, 24, 86, 106). A rapid burning or defoliation may be spectacular, but the effect is short-lived. Over the longer term, overdosing often results in much less kill of the weed population than would the optimal, recommended rate. Foliar-applied systemic herbicides should cause a slow decline of the target weed. The problem should be approached as a long-term one requiring repeat annual or semi-annual treatments at optimum rates until the weed population is negligible. Thereafter, maintenance treatments with low rates of herbicide while the weeds are small are much more effective and efficient than waiting for the weeds to become a problem again.

Coverage

The importance of good coverage of the target plant with the spray material cannot be overemphasized. Herbicides in plants move readily longitudinally but very poorly radially (horizontally). Thus, unless the herbicide is well distributed over the plant canopy, control will be poor(31). Treating one side of the weed will result in injury to that side only. Whether the herbicide is applied at a spray volume rate of 5 gal/acre or 80 gal/acre, good coverage is essential(88). Wetting *per se* is not important; it is only a means to achieve good coverage. (This principle should not be confused with the need of the spray material on the foliage having to remain wet in order for the herbicide to penetrate the leaf cuticle[98].)

Spray volume rates

For maximum efficiency as well as efficacy, spray volume rates (spray volume per acre) must be kept as low as possible while still allowing adequate coverage(58, 68, 103). Water is merely a diluent to make the herbicide spray volume large enough to make uniform distribution possible. Any water beyond the minimum volume needed unnecessarily increases work by requiring more volume to be sprayed and, thereby, more reloadings per acre treated. Fuel consumption and wear of equipment are unnecessarily increased. Efficacy is also reduced because, at any given herbicide rate, dilute sprays are less effective than more concentrated sprays[1, 33, 67, 72, 94]. For these reasons it is essential that herbicides be applied precisely.

Excessively high-volume application is usually the result of

- drenching by the applicator hoping to get better or quicker weed kill
- use of high pressure either to achieve drenching or increase the reach (or "throw") of the spray
- a malfuctioning pressure regulator
- dense brush that slows the speed of the sprayer.

Timeliness

Timeliness of herbicide applications is critical to the effectiveness of the herbicide and to the efficiency of the operation. Herbicide applications should be made when the weeds are most susceptible and when environmental conditions are suitable for effective and safe application. Herbicides should be applied under the following conditions.

1. *When energy reserves in the weeds are low*[53]. This is usually after plants have expended stored energy to fuel new growth, such as after a drought, after winter (at higher, colder elevations), after a fire, or after previous herbicidal or mechanical treatments.

2. *When there are some fully expanded, "soft" leaves*[12, 31, 93]. At this stage, the cuticle is thin, the leaf area is large enough to retain sufficient amounts of the herbicide spray, and, within the plant, downward translocation is active as the weed begins to rebuild energy reserves (carbohydrates).

3. *When the weeds are young.* Small, young plants are easier to control than larger, more mature, or woodier plants[64, 107, 112]. Attacking weeds early in the infestation requires less herbicide and fewer repeat treatments, affords greater mobility, and results in less weed competition. In contrast, allowing weeds to grow too large complicates the weed control operation. Equipment movement is hindered by large, dense brush, particularly in rough terrain where unobstructed vision is critical. Reduced speed tends to increase the spray-volume rate, because the sprayer output remains the same while the application speed is reduced. The greater mass of foliage to be treated also means a higher spray volume rate must be used to achieve complete coverage. Furthermore, directing sprays upward to control tall plants increases the risk of herbicide drift. Timely retreatment, while the weeds are small, reduces the amount of herbicide needed in those subsequent treatments[57, 75].

4. *When the weeds are actively growing.* Weeds should be sprayed when they are actively growing and photosynthesizing. Actively growing plants have leaves that are succulent and readily penetrable by herbicides. Foliar-applied herbicides must be translocated via the phloem out of the leaves and into storage sites in the stems and roots or to the growing points that need the carbohydrates (photosynthate). Translocation in the phloem is "powered" by photosynthesis. Active photosynthesis results in high photosynthate production in the leaves and active translocation of photosynthate via the phloem. Phloem-mobile herbicide absorbed by the leaves moves with the flow of photosynthate. If photosynthesis is active, the flow of photosynthate and phloem-mobile herbicide is strong[11]. If photosynthesis is weak, when the plant is diseased[111], for example, or while it is drought-stressed[14, 72], photosynthesis is weak and the flow of photosynthate and phloem-mobile herbicide decreases or stops.

5. *When it is not raining but soil moisture is adequate.* Maximum uptake of herbicide from the leaf surface into the leaf is influenced by rain. Rainfall too soon after application may wash the herbicide off the leaf surface[20, 23, 42, 117]. The duration of the rain-free period required for maximum efficacy depends on the weed species[97], the herbicide[97], the surfactant[16, 84], the herbicide formulation[23], the rate of application[25, 117], and environmental conditions[35]. On the other hand, spraying should be done when the moisture status of the soil is adequate for vigorous growth. Furthermore, herbicide uptake is facilitated by succulence of the leaves[12, 93, 107, 112]. In hot, dry weather, leaves have a waxier leaf cuticle not readily penetrable by herbicides.

Integrated treatments

Typically, woody plant populations cannot be eliminated by a single spray application. Most woody species have sufficient food reserves that allow them eventually to outgrow the effects of a single herbicide spray application. Thus, repeated or integrated treatments that stress the weeds over a longer period of time are usually required for effective control, particularly for older, more established infestations. For example, two herbicide sprayings a year apart virtually eliminated guava from experimental plots, whereas a single application resulted in the eventual recovery of the weed (44). Similar results were reported for *Rubus* spp. (6, 7), gorse (13, 69), and lantana (40).

Likewise, burning or mechanical control methods that remove most of the plant biomass, followed by a herbicide application early in its recovery, also results in higher weed mortality than a herbicide spraying of undisturbed plants[56, 69]. Topping of woody plants reduces their biomass, forces the plant to tap its food reserves to fuel regrowth, allows better herbicide coverage to be achieved, and provides more succulent leaves, which are more readily penetrated by herbicides. This strategy has been used effectively on lantana[26, 48], *Rubus fruiticosis* (no common name)[6], gorse[54], and on *Solanum auriculatum* (no common name) and turkey berry, species closely related to apple-of-Sodom[100]. Tropical soda apple (*Solanum viarum*) required a mowing followed by triclopyr applications for adequate control[71].

In spraying previously treated plants, the succeeding treatment should not be done too early or too late. When the plant is in early flushing, translocation of carbohydrates upward from the roots to the new flush will prevent the downward translocation of foliar-applied herbicide. Applications should be made when a sufficient number of new leaves have fully expanded. This is when photosynthesis is active and translocation of photosynthate from the leaves is active as the injured plant rebuilds its energy reserves. Waiting too long allows the weed to rebuild its energy reserves.

Climate can be exploited in chemical weed control[53]. In leeward areas subject to seasonal drought, herbicides should be applied early in the rainy season. At this time, energy reserves in plants are low after being tapped to support the new flush after the drought, leaf area is large, and leaves are succulent. After treatment with a selective herbicide, the plants would be defoliated during the wet growing season and would not be able to rebuild their energy reserves before the onset of the next dry season. In the meantime, growth of tolerant species would be unhindered by competition from the weedy plants, and soil moisture would be conserved. In the higher elevations with more uniform rainfall distribution, there is a surge in growth in the spring when temperatures get warmer. This would be the best time to apply herbicides. However, brush in high-rainfall areas tends to exhibit better recovery without the added stress of seasonal drought.

Kona rancher Allen Wall reported that slashing guava in the cool season and spraying the regrowth in early summer (rainy season) before the weed can regain its vigor effectively controlled this weed of humid areas. This strategy integrates climate with mechanical and chemical control methods.

Drift prevention

Herbicides that drift from the target area do not contribute to weed control. More seriously, such herbicides can cause severe damage to nearby crops or other valuable plants. It is the legal responsibility of the applier to prevent herbicide drift. There are six principal factors that increase the risk of herbicide drift.

1. Proximity to sensitive plants. The first precaution in applying herbicides is to be aware of the location of sensitive and valued non-target plants. The applier can then make adjustments in the weed control program to avoid drift hazards too close to non-target plants.

2. Droplet size. Fine droplets have a greater potential to drift than large droplets. High pressure spray and small nozzle orifices yield a greater proportion of “fines” than low pressure and large orifices. However, coarse sprays require higher spray volumes than fine sprays for adequate coverage. The applier therefore must adjust the spray to fit the conditions.

3. Wind. Herbicides should be applied during still times of day. High winds will displace herbicides. Just how great a wind velocity can be tolerated depends on the other factors stated here, but in any case it should not exceed 10 mph, or any wind speed limit stated on the label.

4. Height of spray. The higher the arc of the spray the greater the distance spray can drift. Thus, aiming the spray up toward the canopy of tall brush increases the drift potential, particularly when high pressure (fine mist) and volatile formulations (esters) are used.

5. Formulation. Long distance drift involves herbicide vapor. Ester formulations of herbicides are somewhat volatile. Because of the threat of vapor drift, current ester formulations are manufactured in “low-volatile” formulations. However, even these can pose a threat if mismanaged. For example, applying even “low volatile” esters with a mist blower would greatly increase volatilization into the air.

6. Timely weed control. One of the most effective means to prevent drift is to take care of weed problems early. Most drift problems occur when treating tall brush. By tackling weeds while they are small, the applier can keep the nozzles close to the ground, and thus avert the need to spray upward into the air and the need to use high pressure to increase the reach of the sprayer. Also, lower herbicide rates are needed when the weeds are small.

Calibration of spray volume rate and herbicide concentration

To ensure application of the recommended rate of a herbicide, the applier must determine the spray-volume rate (SVR), i.e., the total amount of material (herbicide plus carrier) to be applied per acre (even if less than an acre will actually be sprayed) because the herbicide rate depends on the SVR. To accomplish this, the applier must calibrate the sprayer. The simplest calibration procedure is to spray a plot of known area to determine the required volume of water that will provide good coverage, spraying at a constant, comfortable speed and low (15–45 psi), constant pressure. Thus SVR =

$$\frac{\text{water sprayed (gal)}}{\text{swath width (ft)} \times \text{distance (ft)}} \times \frac{\text{43560 sq ft}}{\text{acre}}$$

Then, herbicide concentration =

$$\frac{\text{recommended herbicide rate}}{\text{SVR}}$$

Example 1. Boom sprayer

Check each nozzle by collecting the output over a set time and measure the volume. The output of the nozzles should not vary from one another by more than 10 percent.

Assume a boom sprayer with a 20-ft spray width. At a constant speed of 3 miles per hour, the sprayer discharges 4.2 gal of water over 300 ft. Thus,

$$\text{SVR} = \frac{\text{4.2 gal}}{\text{20 ft} \times \text{300 ft}} \times \frac{\text{43,560 sq ft}}{\text{acre}} = \frac{\text{30 gal}}{\text{acre}}$$

For each acre to be sprayed, the recommended amount of herbicide must be diluted with enough water to make a total of 30 gal spray mixture. Assuming 0.5 gal herbicide/acre is recommended, then

herbicide concentration =

$$\frac{\text{0.5 gal herbicide/acre}}{\text{30 gal spray/acre}} = \text{0.017, or 1.7\%}$$

Thus the concentration of herbicide required is 1.7%. With this information, any volume of spray mixture can be prepared.

Example 2. Power sprayer, orchard gun method

1. Measure off a known area.
2. Record the water level in the sprayer tank.
3. Spray the known area uniformly with water as would be done with the herbicide mix using a low, constant pressure and the same nozzle setting as will be used in the application. The larger the area sprayed, the more accurate the calibration.
4. Determine the amount of water used by reading the volume gauge and subtracting that volume from the starting level.

Assuming a known area of 60 x 200 ft and that water use was 22 gal, then

$$\text{SVR} = \frac{\text{22 gal}}{\text{60 ft} \times \text{200 ft}} \times \frac{\text{43,560 sq ft}}{\text{acre}} = \frac{\text{80 gal}}{\text{acre}}$$

Assuming a recommendation of 0.5 gal herbicide/acre:

herbicide concentration =

$$\frac{\text{0.5 gal}}{\text{80 gal}} = \text{0.006, or 0.6\%}$$

Thus the herbicide dilution required is 0.6%.

Example 3: Knapsack sprayer

(BASF no-math version [unpublished handout])

1. Mark off a calibration plot that is 18.5 ft by 18.5 ft.
2. Spray water over the plot and measure the time in seconds to do it: (example: time = 45 sec).
3. At the same constant pressure, by regulator or constant pressure on the handle, spray into a bucket for the same time and then measure the volume of water collected in fluid ounces: (example:volume collected = 25 fl oz). The number of fluid ounces collected is equal to the SVR in gal/acre (example: 25 gal/acre).

Assume that the herbicide label recommends 1 qt (0.25 gal/acre); then, the concentration of herbicide should be:

$$\frac{\text{0.25 gal/acre}}{\text{25 gal/acre}} = \text{0.01, or 1\%}$$

Thus the herbicide dilution needed is 1.0%.

Important note: If the spray volume rate turns out to be too high, repeat the calibration and try to get the spray volume rate lower. This can be accomplished by increasing the speed of application, reducing the sprayer pressure, using nozzles with a smaller orifice, or a combination of these. Boom sprayer volume rates should be about 25 gal/acre, orchard gun sprayers 30–80 gal/acre, and knapsack sprayers 20–40 gal/acre, depending on the size of the target weeds.

Drizzle foliar application

Logistics limit conventional spraying

The greatest cost component in herbicide applications is labor, in part because of the large volume of carrier, usually water, that must loaded, transported, mixed, and sprayed. This is particularly difficult in areas that are remote from water sources or only accessible by foot, i.e., areas that must be treated with knapsack sprayers. In addition, conventional spraying is also laborious because knapsack sprayers have short throws, so the applicator must walk up to each weed treated, and because of the frequency of re-loading that is necessary. Because of this cost and the effort required in conventional spraying, weed control operations may not be performed in a timely manner. This allows weeds to grow larger between treatments and become more difficult to control. On the other hand, a highly efficient method fosters timely weed control and eventually requires less labor and material as weed size and stand density are reduced. The inefficiencies of treating severe weed infestations are thus avoided.

The drizzle method

A cost- and labor-efficient method of herbicide application was developed by Shigeo Uyeda (now retired) for the McBryde Sugar Company, Kauai. Originally called the “Magic Wand” method[76], the drizzle method employs an orifice disk (Spraying Systems orifice plate 4916-20, 0.020 inch diameter orifice recommended) in place of an atomizing nozzle and a fine strainer (100–200 mesh) to keep the orifice clear. A fine jet-stream is ejected (30 psi suggested pressure) through the orifice (Figure 2a, 2b), which breaks up into large droplets that drizzles onto the plants (Figure 2c). The large, sparsely distributed droplets are contrary to the widely accepted concept of an optimal droplet deposition pattern, i.e., very many, very fine droplets[19, 67]. Nevertheless, the drizzle method has proved sufficiently effective and very efficient[73, 75, 76, 77, 79, 80]. Broadcast application is achieved by waving the wand over the target area. Precise spot application is achieved by aiming the wand at the target weed. The drizzle apparatus can also be used in very-low-volume basal bark applications (see *Basal bark method*, below).

Figure 2a. The drizzle method of foliar herbicide application.

Figure 2b. Close-up of drizzle apparatus nozzle.

Figure 2c. Droplet distribution of herbicide applied by the drizzle method.

Efficiency of the drizzle method

The drizzle method is very labor-efficient. The efficiency of the method is derived from its very-low-volume (VLV) application rate (1.6 gal/acre) and a throw of 15 ft. Only small quantities of water have to be loaded, transported, mixed with herbicide, and applied. Downtime is greatly reduced, as relatively few re-loadings are required. The reach of the drizzle applicator means the applier does not have to walk up to each weed as with conventional knapsack spraying. In open pastures, the user walking at 1 ft/sec and waving the wand in a horizontal arc to cover a swath 20 ft wide can broadcast-treat 1 acre in 36 minutes at the application volume rate of 1.6 gal/acre. On trails, the applier with a conventional knapsack sprayer must treat each side of the trail in turn. The drizzle applier can treat both sides of the trail in one pass. A trail 7 ft wide can be treated at 2 mph. On Koaie Trail on Kauai, where clearing 3 miles of trail would have been required 576 worker-hours for manual clearing or 40 worker-hours for conventional spraying, only 4.5 worker hours were required using the drizzle method,(75, 79) and weed suppression was excellent. The greater manpower requirement of conventional spraying results from the higher volume rate that would have required more porters to carry water. This would be exacerbated on trails with few or no water sources. Koaie Trail frequently descended to Koaie Stream. The disparity in cost between conventional spraying and drizzle application would have been even greater where water must be transported over the entire trail, expecially where the trail is rough and steep. The experience of Koaie Trail has been repeated on several other trails on Kauai where mechanical control methods have been replaced by drizzle applications of herbicides and labor requirements have been reduced by 83–98%(73, 75).

Other advantages

In addition to labor efficiency, the drizzle method offers several other advantages:

- Low drift potential—because of the large droplets, drift is minimal.
- Safety—heavy loads are a risk factor in injuries. Furthermore, that risk is compounded by fatigue caused by carrying such heavy loads. This is especially so in rough and steep terrain. Very-low-volume methods reduce the weight and number of loads that appliers and porters must carry. The applier can cover more than an acre with a half-full knapsack.
- Reliability—unlike other more complex very-low-volume equipment, the drizzle method is not subject to breakdowns because it employs ordinary sprayers.
- Cost and convenience—any ordinary knapsack sprayer can be easily and cheaply converted into a drizzle unit and back again. In addition, tank pressure is easier to maintain with a manual knapsack sprayer in a drizzle mode because of the very low output. The drizzle unit is easily deployed, in contrast to heavy power sprayers or crews of laborers for mechanical control. One person on a moment's notice can go off to treat a large area. The convenience of the drizzle method encourages more timely weed control. The resulting lower weed biomass makes succeeding operations easier and with less herbicide required.
- Versatility—the wand of the drizzle unit can be waved to broadcast herbicides, aimed for a very precise spot application and, with a crop oil carrier (see below), used for basal bark treatments. With its reach of 15 ft, it can be used on brambles, weeds to 12 ft tall, and plants over the edge of cliff-side trails.
- Affordability of oil carriers—because of the very low volume of the drizzle method, crop oil carriers are affordable: only 1.3 gal/acre or less is required in broadcast applications. Ester formulations of triclopyr can be applied in a crop oil carrier to treat weeds tolerant of foliar applications of triclopyr in water, such as Mauritius hemp and gorse. Triclopyr in crop oil can also be used in very-low-volume basal bark or stump treatments of susceptible woody species (See *Basal bark method*, below).

Limitations of the drizzle method

For certain weeds, the drizzle method is not as effective as conventional spraying. In addition, the user is limited to liquid herbicides (solutions or emulsions) with labels that allow a high enough concentration to apply an effective amount at a very low spray-volume rate. Wettable powders will clog the strainer or the fine orifice of the disk. There are only a handful of herbicides that are appropriate for drizzle application (Table 1).

Calibration

As in any method of application, calibration is critical to delivering the correct volume and, thereby, the desired herbicide rate. This ensures efficiency, efficacy, economy, and environmental protection. The most convenient set-up is to use an orifice disk with a 0.02 inch orifice at a tank pressure of 30 psi. With a manual knapsack sprayer lacking a pressure regulator, constant pressure can be achieved by maintaining constant pressure on the handle. This will be easy to do because the out-

Table 1. Herbicides for drizzle application.
(Always check labels before use, as they are subject to revision).

Product	Herbicide	Site[1]	Use[2]	Method of application[3]	Concentration[4] (%)
Banvel®	dicamba	P, F, N	B	f	15
Garlon® 3A	triclopyr amine	P, F, N	B	f	20
Garlon® 4	triclopyr ester	P, F, N	B	f, bb	20
Hi-Dep®	2,4-D amine*[5]	P, F, N	B	f	15
MCP Amine®	MCPA	P, F, N	B	f	15
Pathfinder® II	triclopyr ester	P, F, N	B	bb	100
Redeem®	triclopyr amine	P	B	f	20
Remedy®	triclopyr ester	P	B	f, bb	15
Rodeo®	glyphosate[5]	A, N	NS	f	15
Roundup®	glyphosate[5]	P, F, N	NS	f	20
Velpar® L	hexazinone	P, F, N	NS	f, s	67

*Restricted.
[1]A = aquatic, P = pasture, F = forest, N = noncropland. Check label for specific uses.
[2]B = broadleaves or dicots, NS = nonselective.
[3]f = Foliar, bb = basal bark, s = soil.
[4]Suggested concentration based on 1.6 gpa application volume rate. If allowed, higher concentrations may be used. Otherwise, higher herbicide rate requires higher application volume rate, e.g., 3.0 gal/acre or higher. Lower concentrations are sufficient for more susceptible species and for seedlings.
[5]Many brands of 2,4-D and glyphosate are available. Check label for site uses and allowed concentrations. 2,4-D sold in quantities of a quart or less is not restricted.

put is so low that the tank pressure declines very slowly. It really does not matter what pressure is used as long as it is not so high as to atomize the output nor too low to maintain maximum throw. Of course, constant pressure should be maintained not only during calibration but also during the actual application. (To observe the droplet distribution pattern, drizzle a dry paved area, walking at 1 ft per second and covering a swath 20 ft wide). The calibration method described here assumes a spray swath of 20 ft, an application speed of 1 ft/sec, and an SVR of 1.6 gal/acre. Application speed can then be adjusted for narrower swaths, e.g., increasing the speed three-fold for spray swaths of one-third the original calibrated spray width (20 ft). However, to treat very narrow swaths, e.g., a 2-ft swath along a fence line, increasing application speed sufficiently will not be practical, so a smaller orifice disk must be used to provide a lower output and smaller droplets, or the herbicide concentration must be diluted and the SVR increased to obtain the desired herbicide rate.

To calibrate a drizzle unit:

1. Measure the water output of the drizzle sprayer by collecting the discharge for 1 minute at constant pressure. (Because of the low volume, the collected water is best measured in milliliters (ml) with a metric graduated cylinder, or the collection period can be increased to several minutes until a volume measurable in a metric measuring cup is collected):

$$\frac{\text{Volume collected (ml/min)}}{\text{60 sec/min}} = \text{Output (ml/sec)}$$

2. Divide output by 3785 (ml/gal) to convert output to gal/sec:

$$\frac{\text{Output (ml/sec)}}{\text{3785 ml/gal}} = \text{Output (gal/sec)}$$

3. A swath 20 ft wide and 2178 ft long covers one acre. At a walking speed of 1 ft/sec, it would take 2178 sec to treat 1 acre.

$$\frac{\text{43560 sq ft/acre}}{\text{20 sq ft/sec}} = \text{2178 sec/acre}$$

4. Multiply (2) by (3) to get the spray volume rate in gal/acre:

$$\text{Output (gal/sec)} \times \text{2178 sec/acre} = \text{SVR (gal/acre)}$$

Alternatively, the equations above can be summarized to calculate the SVR for applicaations 20 ft wide and an application speed of 1 ft/sec:

$$\text{Output (ml/min)} \times 0.0096 = \text{SVR (gal/acre)}$$

5. Determine the concentration of herbicide by dividing the recommended herbicide rate by (4), the SVR:

$$\frac{\text{0.25 gal herbicide/acre (example rate)}}{\text{1.5 gal/acre (example SVR)}} = 0.17\text{, or } 17\%$$

6. Determine the speed to treat narrower swaths, such as a trail, from Step 4. Treating a narrower swath than the 20-ft one calculated in Steps 1–4, for example, 7 ft, requires a greater application speed to maintain the same SVR:

$$\text{1 ft/sec} \times \frac{\text{20 ft}}{\text{7 ft}} = \text{2.86 ft/sec, or 3 ft/sec}$$

Drizzle foliar application, water carrier

Herbicides soluble or miscible in water can be drizzled over weeds at the appropriate concentration. In broadcast applications, the wand should be aimed over the target plants and waved to achieve uniform distribution. The wand can be waved in a circular motion or looped in mid-swing to avoid underdosing the middle and overdosing the edges of the swath as the wand slows at the ends of the swing before its direction is reversed. The basic principles of herbicide application apply to drizzle application as they do to conventional spray applications. There should be uniform distribution of the droplets over the whole canopy of the target weed without overdosing. Taller weeds are a problem because the lee side of the plant would be underdosed. These can be treated from two opposite sides to ensure complete coverage. However, it would probably be more economical instead to re-treat in a few months when there is a new flush of growth and with the canopy thinned out by the previous treatment. After the standing weed population has been eliminated, reinfestations should be re-treated when the weeds are small, semi-annually or annually depending on the climate. At this time the weeds will be more susceptible and lower herbicide rates can be used. Thus over time the amount of herbicide required will diminish. For example, in annual applications on Koaie Trail on Kauai, the second application required only 41 percent as much herbicide as the first application, 39 percent on the third, and 25 percent on the fourth[75].

Weed species susceptible to drizzle-applied triclopyr include highbush blackberry, yellow Himalayan raspberry, catsclaw, Formosan koa, bur bush, sacramento bur, melastoma, Indian pluchea, and sourbush. Weeds susceptible to glyphosate are lantana, guineagrass, Jobs tears, Californiagrass, palmgrass, fountaingrass, and huehue haole.

Drizzle foliar application, crop oil carrier

Certain weeds that are tolerant of herbicides in water carrier may succumb to herbicides in an oil carrier. Nonphytotoxic crop oil can be used as a carrier with the ester formulation of triclopyr. The oil, which contains emulsifiers to make mixing with water possible, is harmless to plants but helps oil-soluble herbicides penetrate leaves and stems and thereby increases efficacy. Crop oil may also be used as an adjuvant at 0.5–20%. When using oil as an adjuvant, the herbicide and oil should be mixed first, then added to water and made to volume with more water. Gorse and Mauritius hemp are examples of weeds tolerant of applications of triclopyr ester in water but susceptible to the same herbicide in a crop oil carrier.

Cut-surface methods

Notching

A very effective albeit labor-intensive way to chemically control brush and trees is to mechanically penetrate the bark and place the herbicide directly into the sapwood (xylem) of the plant (Figure 3). The herbicide is then translocated throughout the plant, provided that the target plant has actively functioning leaves. Specialized equipment such as tree injectors may be used to pierce the bark and deposit the herbicide. However, a simple method requiring no specialized equipment is the “notching” or “hack and squirt” method. In this method, notches an inch or so deep into the sapwood are made every 4 inches around the trunk with an ax or machete. Because herbicides do not move radially (horizontally) in the plant very well, the herbicide must be placed in wounds made at intervals around the circumference of the trunk. Herbicides applied to a single notch will translocate vertically and likely kill only that vertical segment of the plant. The wound is cut at a 45° angle to form a receptacle to retain the herbicide, and the bark is pried away from the trunk to increase the area of herbicide contact with the sapwood. The notches should be made as close to the ground as possible to enhance suppression of buds at the root crown,[58, 61] although this is not necessary with all species[96]. A study done in Australia demonstrated that herbicide applications to wounds made by

Figure 3. Cut-surface (notching) herbicide application. Notches must be made around the stem.

puncturing the trunk with a narrow bladed instrument gave better kill than did slashing it with a machete[95]. This was attributed to better penetration into the sapwood by the narrow blade. Although the machete caused a longer cut, only a short section of the blade actually reached deep into the sapwood. Also, the narrow-blade wound probably retained more herbicide. Herbicides tended to run out of the edges of machete cuts. In trees that fork close to the ground, it would also be a good idea to notch each branch on the inside of the crotch to improve distribution of the herbicide within the aerial portion of the tree.

Notching is very effective on dicot species that have one or a few trunks, provided a suitable herbicide is available. Obviously, this method would be difficult on shrubs with many fine stems. Trees of 8-inch trunk diameter can be treated at a rate of 21 per worker-hour[82, 83]. Because each plant is treated individually, there is little likelihood of injury to non-target plants.

For species somewhat tolerant of the herbicide used, notches can be made end-to-end in a continuous ring around the trunk (frilling)[61, 87]. This in effect doubles the applied dose[95]. For larger trees, drilling holes into the trunk allows a higher dose to be applied (Figure 4a, 4b). For example, spaced notches treated with dicamba or glyphosate were inadequate to kill large roseapple trees. However, excellent control was obtained with the same herbicides when 4 ml of either was applied to drilled holes, 0.5 inch in diameter by 3–4 inches deep. The holes were drilled at a downward angle every 10 inches around the base of the trunk[43, 44].

The best herbicide to use in notching depends on the weed to be treated. Any of the brush-killers could be appropriate. The salt formulations are preferable to the esters because they are translocated more readily, although the latter are usually satisfactory[49, 61, 95]. In addition to the brushkillers, glyphosate is very effective on several species (e.g., fayatree, karakanut, paperbark, and roseapple) when applied by the notching method or to drilled holes.

The amount of herbicide that should be applied varies with weed species. The recommended rate is usually 1 ml per notch or 4 ml per drilled hole of the concentrated herbicide or of herbicide diluted as much as 20 times. At 1 ml of concentrated herbicide per notch, 1 fl oz of herbicide is sufficient to treat 28 notches. There is no particular advantage to diluting the herbicide, except for economy in those cases where the diluted herbicide is potent enough to kill the plant. The notches can hold only a limited volume of herbicide; some of it will leak out from the edges of the notch. More concentrated solutions allow more herbicide to be absorbed into the xylem. However, some herbicide labels dictate the concentrations that may be used. Should the label require dilution, mix only enough for one day's needs, because dilution with water will accelerate degradation of the herbicide.

Figure 4a. Drilling holes to treat a large tree.
Holes about ⅝ inch diameter by 3½ inches deep must be made at downward angle at 12-inch intervals around the trunk.

Figure 4b. Applying herbicide into drilled holes.
Apply 3–4 ml of herbicide concentrate to each hole, unless otherwise directed by the label.

Cut-stump method

A variant of the cut-surface treatment, the cut-stump method, is useful in dry areas where there is a need to clear standing vegetation. The plant is cut down and concentrated herbicide is immediately applied to the sapwood of the stump (Figure 5). It is essential that the application be made immediately after cutting, because the sap in the sapwood will recede into the stump, drawing down the herbicide with it into the region of the root crown where shoots originate. Waiting even a few minutes allows air into the sapwood and blocks the entry of the herbicide, much as a vapor lock in a fuel line blocks

Figure 5. Herbicide application to cut-stump surface.
Application of herbicide concentrate should be made immediately after felling. Works best in dry season.

the flow of fuel[49]. This method may not work in high-rainfall periods because the sap will ooze out of the stump and keep the herbicide from entering the sapwood[44].

Basal bark method

The basal bark method is very effective for killing large shrubs and small trees[28, 58]. However, like notching, it is labor-intensive because each plant must be individually treated. The high-priced oil carrier also adds to the expense. This combined high cost of material and labor restricts the utility of the basal bark method to small populations of hard-to-control species or other special situations requiring sure "kill" or protection of nearby non-target plants that would be injured by foliar spray drift.

In the basal bark method, an oil-soluble formulation of a suitable herbicide and a light oil are used to penetrate the bark. This solution, 2–8% herbicide in oil, is sprayed or brushed onto the base of the trunk of the target plant. The trunk is wetted from about the 20-inch level down to the soil line (Figure 6). Effective control requires that the entire circumference of the trunk be treated. Misses along the trunk circumference could allow buds to sprout[36]. There should be a little runoff to wet the soil around the base of the trunk to ensure that the root crown, which is an active zone of bud formation, is adequately treated. Plants susceptible to basal bark treatments would be even more susceptible to stump bark treatments with the same oil-herbicide treatment (Figure 7).

The oil used as the carrier should be a light oil such as diesel, kerosene, or a crop oil made specifically for this purpose, which is capable of penetrating the essentially waterproof bark. Heavy oils such as motor oil or gear oil are not as effective in penetrating the bark, and use of used motor oil would be illegal. Crop oil, a highly refined oil, is less toxic than fuel oils and is nearly odorless. For basal bark treatments, water is useless as a carrier because it cannot penetrate the bark.

The herbicides used in basal bark treatments must be oil soluble, either esters or long-chain amine salts. Triclopyr, 2,4-D, and related herbicides are available in ester formulations and are thus registered for basal bark treatments, along with some salts, such as imazapyr, that can be mixed with oils. Although the effectiveness of 2,4-D against woody plants is limited, there are a few species against which 2,4-D in basal bark treatments is useful. However, it is very effective on stumps of many species, even though it may not be effective on standing trees of the same species. For non-crop and forest uses, imazapyr in oil is an effective basal bark and stump treatment.

Figure 6. Basal bark herbicide application.
Apply herbicide-oil solution completely around the stump from ground level to 18–24 inches.

Figure 7. Stump-bark herbicide application.
Apply herbicide-oil solution to the bark completely around the stump. This is usually the most effective method to kill woody plants.

Very-low-volume basal-bark and stump applications

Ester formulations of triclopyr may be mixed in oil at 20% or more and applied as thin-line or very-low-volume applications to control woody plants (Figure 8) and to kill stumps (Figure 9). Triclopyr ester may also be used as the concentrate in this way. Low-output equipment must be used to avoid overdosing. On larger plants, applications should be made at least on two opposite sides of the basal stem. Susceptible species are young plants with juvenile bark and those species with thin bark, such as strawberry guava, Molluca albizia, gorse, catsclaw, and velvet tree. Downy rosemyrtle, Formosan koa, and melastoma are also susceptible but require applications from two sides. Large trees and species with thick, corky barks cannot be controlled by this method (e.g., paperbark, java plum). Applications to stumps or to resprouting stumps should be very effective (Figure 9).

Soil-applied herbicides

Some pre- and postemergence herbicides are applied to the soil and taken up through the roots of target plants. Three granular or pelleted herbicides are registered for use in Hawaii: dicamba (Veteran® 10-G [BASF]), hexazinone (Velpar® and Pronone Power Pellets® [DuPont]), and tebuthiuron (Spike® 20P [Dow Agrosciences]). Dicamba and tebuthiuron selectively control broadleaf weeds. Hexazinone, also available as a wettable powder and a liquid concentrate, is nonselective but may be applied selectively in spots at the base of plants or in grid patterns (hot spots) in larger infestations. While grasses are killed at the small application spots, no major damage to the grass sward is incurred. The roots of broadleaves that feed where the hexazinone hot spots are will absorb the material, which then kills them.

Because of its low animal toxicity and poor mobility in soils, tebuthiuron is an environmentally safe her-

Figure 8. Very-low-volume basal bark herbicide application.
Apply oil-herbicide solution in horizontal or vertical streaks. Works best on thin-barked species and plants with juvenile bark.

Figure 9. Very-low-volume herbicide application to stump bark.
Apply oil-herbicide solution in streaks around the stump bark.

bicide. It is active against guava, koa haole, apple-of-sodom, and christmasberry, although larger plants may be more tolerant[47, 74]. Control of fayatree, Formosan koa, gorse[46, 48], and downy rosemyrtle with tebuthiuron (Univ. Hawaii, unpublished data) has been poor. It is important to apply the proper amount of any granular herbicide. The material is expensive, and grass can be injured by an overdose. Note that with Spike 20P (tebuthiuron), 10 lb/acre is equivalent to only 2 pellets per square foot.

Dicamba, an excellent foliar herbicide on polygonaceous weeds (spiney emex, kamole) and on guava and other species, has not shown much promise on Hawaii's woody plants in the granular formulation[45, 46].

Hexazinone is a persistent and mobile herbicide that is of low animal toxicity. It would pose no groundwater contamination threat when used sparingly, particularly in drier areas. Because it is nonselective, it should not be used in broadcast applications over large areas in any case. Although hexazinone is very effective on most weeds, the efficacy of it and tebuthiuron have been erratic against weeds in small-plot soil applications in forests (Univ. Hawaii, unpublished data).

Appendix 1
Herbicides Registered for Use in Pastures and Natural Areas of Hawaii

This appendix lists and describes some of the herbicides registered for weed control in pastures and ranges in Hawaii. The primary source of the information on herbicide properties is the Herbicide Handbook of the Weed Science Society of America, 7th edition[113, 114] and the list of registered herbicides provided by the Pesticides Branch of the Hawaii Department of Agriculture. In addition, some information was obtained from labels and technical sheets issued by the manufacturers. Because of constant changes in registration and labels, the user is responsible for verifying that the information in this publication is current.

Explanation of herbicide description

Use

"Use" refers to situations and types of weed infestations where the herbicide may be useful. "Selectivity" refers to the capability of the herbicide to kill one type of plant, usually the weed, but not another. "Preemergence" means before the newly planted desirable plants or weeds or both emerge from the ground; "postemergence" means after these plants are up. Some herbicides may be effective both preemergence and postemergence.

Formulations

Herbicides are of several different types of formulations. Herbicide manufacturers and formulators design these formulations based on chemical properties, intended use, and customer demands. Some of these formulations are:

Water soluble solids. These powders or crystals can be dissolved in water for application. The mixture is a true solution; the solutions are clear.

Water soluble concentrates. These liquid concentrates, usually salt formulations, can also be dissolved in water to form true solutions.

Emulsifiable concentrates (EC). These are oil-soluble products that are formulated with emulsifiers so they can be diluted with water. The resulting emulsions are not true solutions. The oily herbicide is dispersed as micro-droplets in the water carrier, forming a milky emulsion. The emulsion will begin to separate into its water and oil components if allowed to stand without occasional agitation. Emulsifiable concentrates can be dissolved in oil for basal bark applications or to enhance foliar uptake, if allowed by the label. Herbicides in EC formulations are slightly volatile. They may vaporize from spray droplets and plant and soil surfaces, especially in hot weather, and they may injure non-target plants downwind. However, current formulations are "low-volatile" which means the tendency to volatilize is greatly reduced compared to the old ester formulations. Still, greater precautions must be taken with esters than with non-volatile formulations.

Wettable powders. Wettable powders are mixtures of insoluble herbicides in clay and surfactants that can be mixed with water to form a suspension (solids suspended in water). The suspension requires constant agitation to prevent settling. For this reason, wettable powders must not be used without an agitator in the tank. Similar formulations are the flowables and dry flowables. The flowable is a pre-slurried form of the wettable powder designed for easier handling. The dry flowable or dispersable granule is designed for "dustless" handling. Both also require vigorous agitation during application to prevent settling. Wettable powders and its variants contain 60–90% of the herbicide.

Granules/pellets. Granulated material, except dispersable granules, are designed for dry soil application. Such herbicides must be rather persistent and readily absorbed by roots. They are applied by hand, mechanical spreaders, blowers, or aircraft. Granules and pellets for direct application to the soil are of low concentration, 2–20%.

Products

Some herbicides are manufactured or formulated by several firms; each has its own brand name. Others, still protected by patent, may have only a single manufacturer but several brand names. Manufacturers may use variants of a brand name on different formulations of the same herbicide and on mixtures in which the herbicide is used. For example, Tordon 22 K (Dow AgroSciences) contains only picloram, but Tordon 101 (Dow AgroSciences) is a mixture of 2,4-D and picloram. The user should be aware of the content of the product when buying a herbicide. Different brands of the same herbicide may have different registered uses. The applier cannot assume that different brands, even of the same herbicide and formulation, can be used in the same way.

Application
Listed under this subheading are the approved application methods of the herbicides under discussion. Be aware that different brands of the same herbicide may allow different application methods, so the labels of the herbicide being considered for use must be read.

Behavior in plants
Plants absorb herbicides via the foliage, the roots, or both, depending on the characteristics of the chemical. Most herbicides are systemic, i.e., once absorbed by the plant, they must be translocated to some site where they affect the plant. Herbicides travel downward from the leaves to the roots via the phloem and upward from the roots via the xylem (called "sapwood" in woody plants). Some herbicides are restricted to one transport system or the other, others are immobile, and still others travel more or less freely in both systems. (Many herbicides that are phloem-mobile in foliar application can be applied cut-surface into the xylem). This chemical characteristic also influences how herbicides are managed.

The mode of action of herbicides varies. Plant hormones cause rapid but abnormal growth, photosynthetic inhibitors shut down photosynthesis, contact herbicides disrupt cell membranes and cause plants to dry up, inhibitors of cell growth and division cause stunting, inhibitors of respiration cause the plant to use up its stored energy, and inhibitors of biochemical synthesis cause collapse of the plant. The symptoms produced are clues to whether the herbicide is working or not and whether it is the cause of non-target plant injury.

Behavior in soils
Two characteristics of herbicide behavior in soils are important in herbicide management: persistence and mobility. Mobility, in turn, depends on how tightly the herbicide is adsorbed by or adheres to soil particles. A herbicide resistant to degradation (persistent) will be active longer both in the soil and in plants. If it is also mobile, it may cause problems by moving with water out of the target area and injuring plants in non-target areas or getting into the groundwater. A non-persistent, mobile herbicide, however, will degrade before it can travel out of the target area or into groundwater. A persistent, immobile herbicide will stay in place until it is eventually degraded.

The "half-life" of a herbicide is the time required to detoxify half of the herbicide present in an ecosystem; this is the standard measure of persistence. Degradation of pesticides is faster in warm, moist soils and slower in cold, dry soils. In general, herbicide leaching is more of a problem in high-rainfall areas than dry areas and in sandy soils than in soils high in clay and organic matter content.

Toxicity
Pesticides must undergo rigid toxicity tests to determine their safety. Listed under this heading is the acute oral LD_{50} of the herbicide for rats. Although only results on rats are given, the testing protocol requires various tests on fish, birds, dogs, and other animals to develop the toxicology profile of the herbicide. "LD_{50}" refers to the amount of material in mg per kg of bodyweight of the test animal that is required to kill 50 percent of the sample population. The toxicity rating scale is listed in Table 2, along with some example pesticides and common non-pesticidal products as a frame of reference (note that the higher the LD_{50}, the lower the toxicity).

Regulations
Pesticides are categorized into two groups for regulatory purposes: "restricted use" and "unrestricted." Application of restricted use chemicals requires that the applier or the applier's supervisor be certified to apply restricted pesticides. The "restricted" category is assigned to chemicals not only because of hazard to humans and animals but also for potential hazard to non-target plants and contamination of the environment. Picloram, for example, is restricted because of its hazard to non-target plants and to groundwater, but it is of very low animal toxicity. Unrestricted chemicals may be purchased and used by persons without certification. Regardless of classification, however, any pesticide use must be consistent with its label directions.

For a pesticide to be used legally in Hawaii, it must be licensed for sale and it must be registered for the intended use. Some pesticides and uses may be national; that is, they can be used in all states. Some pesticides and uses may be restricted to one or more states. Registrations are specific for a single brand-name product. Thus a new brand of 2,4-D must be newly registered for use and sale. Different brands or different formulations of the same herbicide may have differences in the label that makes one method of application legal with one product and illegal with another, even though the active ingredient is identical.

Grazing restrictions mandate how long animals must be kept off treated pastures or how many days before

Table A-1. The rating scale of toxins and example substances.
Each pesticide product is assigned a signal word to warn users of its toxicity. The signal words (printed on the label) and their approximate hazards are listed in Table 3.

Toxcity rating	Category	Oral LD_{50} (mg/kg bodyweight)	Example (with LD_{50})
1	Extremely Toxic	< 5	Parathion (2)
2	Very Toxic	5–49	Vitamin D (10), dinoseb (40)
3	Moderately Toxic	50–499	Nicotine (50), paraquat (150), caffeine (200)
4	Slightly Toxic	500–4999	2,4-D (700), aspirin (750), bleach (2000), triclopyr (2140), table salt (3320)
5	Almost Non-toxic	5000–14,999	Glyphosate (5000), picloram (8200)
6	Non-toxic	$15,000^{+}$	

slaughter the animal must be removed from treated pastures. Grazing restrictions are more severe for lactating dairy animals than for meat animals. The restrictions are aimed at preventing herbicide residues from contaminating milk and meat. Herbicides applied according to label directions do not represent a threat to animal health.

Included in this listing are herbicides for pastures and natural areas. For aquatic sites refer to Vandiver[109]. Pesticides labels and regulations are frequently changed, so it is the responsibility of the user to read and heed the label to ensure compliance.

Table A-2. Pesticide toxicity signal words and approximate lethal dose.

Signal word	Amount needed to kill a 150-lb human
DANGER	1 teaspoon or less
WARNING	1 teaspoon to 1 tablespoon
CAUTION	1 ounce to 1 pint

Clopyralid

Transline®, amine salt (Dow AgroSciences)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Selective postemergence control of annual and perennial broadleaves in pastures and natural areas. Especially effective on most legumes and composites, including Madagascar ragwort (fireweed). Effective on *Prosopis* species in the U.S. Southwest.	Foliar at 0.5 lb/acre (l.3 pt), at up to 40 gal/acre spray-volume-rate.	Readily absorbed by foliage and roots. Translocates primarily in the phloem, accumulating in growing points in stems and roots. Hormone type herbicide. Causes bending and curving, swelling of stems, elongation, leaf curling, chlorosis.	Low adsorpitivity, moderate leaching. Not volatile or photodegraded. Degradation by microbes. Half-life 12–70 days in a range of soils.	Low toxicity to fish and birds. LD_{50} for rats >5000 mg/kg.	Unrestricted. Grazing: Livestock from treated areas should be grazed for seven days on untreated pastures before moving onto broadleaf crops areas. Livestock droppings may have enough unaltered clopyralid to injure broadleaf crops.

2,4-D

Although the following comments are specific for 2,4-D, related phenoxys MCPP and 2,4-DP have similar properties. MCPA is listed separately. These compounds are often used in commercially formulated mixtures.

Amine salt formulations:

Clean Crop Amine® (Platte)
Formula 40® (Rhone-Poulenc)
Hi Dep Broadleaf Herbicide® (PBI Gordon)
Saber® (Platte)
Savage® (Platte)
Weedar 64® (Nufarm)
Wibur-Ellis Amine 4® (Wilbur-Ellis)
Others
Mixtures

Ester formulations:

Clean Crop Low Vol 4® (Platte)
Esteron 6E® (Vertac)
Salvo® (Platte)
Weedone 638® (Nufarm)
Wilbur-Ellis Lo Vol-4® (Wilbur-Ellis)
Others
Mixtures

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Controls many herbaceous and some woody broadleaves in pastures and natural areas. Established grasses very tolerant except for some lawn species. Sensitive species: guava, joee, Madagascar ragwort, morningglory, tropic ageratum.	Foliar spray, basal bark (esters only), and cut-surface (injection, notching, cut-stump).	A postemergence foliar herbicide, 2,4-D is translocated primarily in the phloem, accumulating in the growing points of stems and roots. Its effect is hormonal; it causes rapid but abnormal growth. The stems and leaves of treated plants curve extremely and leaves become chlorotic before death of the plant.	Applied at conventional rates, 2,4-D toxicity to plants dissipates in l–4 weeks in warm, moist soils. Although somewhat mobile in soils, ready degradation prevents leaching beyond 6 inches.	Low order of toxicity. Acute oral LD_{50} for rats is 300–1000 mg/kg. Chronic toxicity: 2 years feeding trials on rats and dogs produced no effect. Readily excreted by animals.	Restricted, drift hazard, except for quantities of one quart or less, regardless of concentration and number of units purchased or used. Grazing: for lactating animals on pastures treated with up to 2 lb/acre, 7 days withholding. For meat animals, no withholding, but remove animals from pastures treated with 2 lb/acre 3 days before slaughter.

Dicamba

Banvel®, amine salt; Clarity®, DGA salt; Veteran® 10G (BASF)
Vanquish®, DGA salt (Syngenta)
Mixtures

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Postemergence control of broadleaf weeds including some woody plants in pastures and natural areas. Polygonaceous weeds (kamole, spiny emex) are very sensitive. Bur bush, christmasberry, false elephantsfoot, guava are sensitive.	Foliar spray, 0.25–8 lb/acre in SVR of 2–40 gal/acre. Cut-surface	Absorbed by foliage and roots. Translocates readily in xylem and phloem. Hormone type herbicide, causes curving, bending of stems, curling of leaves. Accumulates in growing points in stems and roots.	Low to medium leaching potential in soils but half life is less than l4 days in warm moist soils.	Low toxicity to fish, birds and mammals. LD_{50} rats: 2629 mg/kg.	Unrestricted. Grazing: For lactating animals on pastures treated with ≤½ lb/acre, 7 days withholding; 1 lb/acre, 21 days; 2 lb/acre, 40 days; and 8 lb/acre, 60 days. For meat animals, no withholding but remove animals from pastures treated with ≥2 lb/acre 30 days before slaughter.

Fluazifop-p-butyl

Fusilade DX® or Fusilade II®

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Selective annual and perennial grass control in non-food areas. No activity on dicots. Grass growth retardant at low rates.	Postemergence foliar application at 0.25–0.375 lb active/acre, 1–1.5 pt/acre. Apply with crop oil adjuvant.	Rapidly absorbed, rainfast in 2 hr. Translocates slowly in phloem towards growing points. Cuts off synthesis of fatty acids and thus membranes in grasses.	Low adsorptivity but average half-life in soils 15 days so low risk of groundwater contamination.	LD_{50} in rats 4096 mg/kg, low toxicity.	Unrestricted. Do not graze treated areas. Do not apply through irrigation systems.

Glyphosate

Roundup Original®, Roundup Pro®, Roundup Ultra®; Rodeo® for aquatic and upland sites (Monsanto)
Several new products by Monsanto and other companies now available.

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Nonselective but especially effective against grasses in pastures, natural areas, aquatic sites. Controls sedges, herbs, emerged aquatics by foliar application. Severely injures woody plants by foliar application, though not usually as effective as hormone-type herbicides, except on lantana. Several woody species very sensitive to cut-surface treatments, including Chinese banyan, karakanut, paperbark, roseapple.	Foliar spot spray and cut-surface in pastures and forests. Broadcast spray in forests and in pastures for pasture renovation.	Absorbed through foliage. Rainfall within six hours of application may wash glyphosate off the foliage and reduce effectiveness. Translocated readily in phloem. Mode of action: disrupts synthesis of aromatic amino acids and thus of proteins. Symptoms slow to appear.	So strongly adsorbed to soils as to render it inactive immediately. Poses no ground water contamination threat. Readily decomposed by soil microorganisms. Because of strong adsorptivity, half-life in soil 47 days but non-phytotoxic.	Low toxicity. Oral LD_{50} for rats 4900 mg/kg. Chronic toxicity studies on rats and dogs fed up to 300 ppm per day for 2 years produced no effects.	Unrestricted. Grazing: For lactating animals, withhold 14 days after spot application, 56 days after broadcast application. For meat animals, one day withholding after spot application, 56 days after broadcast application.

Hexazinone

Velpar 90W®, 90% wettable powder (DuPont)
Velpar L®, 25% miscible liquid (DuPont)
Pronone Power Pellets®, large pellets for grid applications (DuPont)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Nonselective control of weeds in pastures and noncropland. Selectivity is achieved by directed spray applications and by "hot spot" applications to the soil near the target weed where the roots can absorb the herbicide.	Apply Velpar L in spots to the soil with an exact delivery gun applicator within 3 ft of stem at 2–4 ml per inch stem diameter, not to exceed 0.33 gal per acre per year (300 1-inch stem equivalents per acre). Where multiple applications are required, apply at opposite sides of plant. Do not apply to standing water, irrigation ditches or marshes as hexazinone is very soluble. Do not apply to thick clay soils. Do not apply near desirable plants (within a distance equal to 3 times the height or canopy diameter, whichever is greater). Both Velpar L and Velpar 90W may be applied to the foliage of target plants in spot application. However, the sprayed area will remain bare for several months. Pronone Power Pellets may be applied in 3-ft grid applications to target one or more plants.	Absorbed by roots and foliage. Translocates via the xylem. Inhibits photosynthesis.	Mobile and sufficiently persistent (half-life 90 days) to have potential for groundwater contamination in high rainfall areas.	Low toxicity to fish, wildlife and mammals. LD_{50} rats l690 mg/kg.	Unrestricted. Grazing: withhold for 30 days after application.

Imazapyr

Arsenal® (BASF)
Chopper® (BASF)
Chopper RTU®, ready-to-use (BASF)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations	Precautions
Nonselective preemergence and postemergence control of grass and broadleaf weeds in forests and wildlife openings.	Foliar 1 lb active/acre, basal bark, stumps.	Readily absorbed via foliage and roots. Translocates via xylem and phloem. Interferes with synthesis of proteins.	Strongly adsorbed in acid soils and high clay and organic matter soils. Does not leach. No runoff into forest streams. Rapidly degrades in shallow ponds.	Low toxicity to fish, wildlife and mammals. LD_{50} rats, 5000+ mg/kg.	Unrestricted.	Weeds can develop cross resistance between sulfonylureas (e.g., metsulfuron, sulfometuron) and imidazolinones (e.g., imazapyr) if any one or combination of these types of chemicals are used repeatedly over 4–6 years. These herbicides should be alternated with herbicides with different modes of action.

MCPA
MCP Amine 4® (Clean Crop)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Selective control of broadleaf weeds (e.g., joee, Madagascar ragwort, tropic ageratum,) and some sensitive woody weeds such as guava in pastures, forests and non-crop areas.	Foliar, 1-2 lb/acre and cut surface in pastures. Non-crop land up to 3 lb/acre. Legumes sensitive.	Readlily absorbed by leaves. Phloem mobile.	Not persistent. Mobility not a problem given short half-life of 6 days in warm, moist soils.	Slightly toxic. Oral LD_{50} in mice 650 mg/kg bodyweight.	Unrestricted. Remove meat animals to be slaughtered from treated land one week before slaughter or after MCPA application. Do not graze milk animals on treated land within 1 week of treatment.

Metsulfuron
Escort®, 60% dry flowable (DuPont)
Ally®, 60% dry flowable (DuPont)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Selective control of dicots in pastures and noncropland. Kahili ginger, yellow ginger and white ginger very sensitive (0.5 oz. product / acre).	Foliar spray 0.06-0.45 oz active/acre, with an effective surfactant, in 20-100 gal/acre. Very low doses effective. Extreme precautions should be taken to prevent drift and in cleaning equipment. Weeds can develop cross resistance between sulfonylureas (e.g., metsulfuron, sulfometuron) and imidazolinones (e.g., imazapyr) if any one or combination of these types of chemicals are used repeatedly over 4-6 years.	Readily absorbed by foliage and roots. Translocates readily in the xylem and less so in the phloem.	Adsorption to clays is low; leachable, but biodegradation is rapid. Half-life is l-6 weeks.	Low toxicity to fish, wildlife and mammals. LD_{50} rats >5000 mg/kg.	Unrestricted. No grazing restrictions.

Paraquat
Ortho Paraquat® CL (Chevron)
Gramoxone® (Zeneca)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Non-selective. Apply as foliar spray for suppression of existing vegetation e.g., for pasture renovation. Mature plants readily recover from treatment.	Foliar spray.	Very rapidly absorbed by foliage. Very resistant to washing by rain. Mode of action: Contact. Destruction of cell membranes in the presence of sunlight. No breakdown of paraquat in plants.	Strongly and immediately adsorbed to clay minerals in soils. Soil-bound paraquat is persistent but biologically inactive. It will be slowly degraded.	Moderately toxic, acute oral LD_{50} in rats is 120 mg/kg. Chronic toxicity trials, 2 years at up to l70 ppm paraquat per day produced no effect in rats.	Restricted use, irreversibly toxic if swallowed. Special permit from the Hawaii Department of Agriculture required.

Picloram

Tordon 22K®, potassium salt (Dow AgroSciences)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Woody plant control, foliar and cut-surface applications in pastures. Grasses tolerant, cruciferous plants (cabbage family) tolerant. Wide spectrum of dicot species susceptible including black wattle, cactus, catsclaw, christmasberry, gorse, lantana, faya tree, hilahila, java plum, koa haole, roseapple.	Foliar spray, cut-surface application.	Readily absorbed by foliage and by roots. Ready translocation in xylem and phloem. Mode of action: hormonal.	Can be persistent, half-life 20-300 days, and mobile in sandy, low organic matter soils. Because of persistence, extreme caution should be exercised to avoid drift and other forms of contamination of cropland and similarly sensitive non-target areas. This includes keeping livestock grazing recently treated pastures from cropland. Picloram will pass through animals rapidly and unaltered. Picloram is sensitive to photodecomposition.	Low order of toxicity. Oral LD_{50} for rats is 8200 mg/kg. Chronic toxicity trials (2 years, I50 mg/kg/day) on rats and dogs produced no effects.	Restricted use. Special permit from Hawaii Department of Agriculture required. Spot spraying only. Hazard to non-target plants, groundwater contamination potential. Grazing: For lactating animals 14 days withholding. For meat animals on pastures treated with up to 1 lb/acre no withholding, but remove 3 days before slaughter during the 2 weeks following treatment.

Sulfometuron

Oust®, dispersable granules (DuPont)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Precautions
Nonselective preemergence and postemergence control of weeds in natural areas.	Foliar 2.25–8 oz active/acre.	Absorbed via roots and foliage. Translocates in both xylem and phloem. Inhibits protein synthesis.	Mobility in acid soils and high organic matter soils poorer than in alkaline soils and low organic matter soils. Soil half-life in acid soils 20–28 days.	Low toxicity to fish, birds and mammals. Oral LD_{50} in rats greater than 5000 mg/kg.	Because sulfometuron is effective at low rates, avoid drift and application to bare soil where wind can blow treated soil onto sensitive plants. Weeds can develop cross resistance between sulfonylureas (e.g., metsulfuron, sulfometuron) and imidazolinones (e.g., imazapyr) if any one or combination of these types of chemicals are used repeatedly over 4–6 years. These herbicides should be alternated with herbicides with different modes of action.

Tebuthiuron

Spike 20 P®, pellets (Dow AgroSciences)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations	Precautions
For control of dicots including woody plants by soil applications in pastures and wildlife openings. Effective on christmasberry, guava, strawberry guava, koa haole, Madagascar ragwort, shoebutton ardesia. Poor on downy rosemyrtle, fayatree, Formosan koa, gorse.	Application of granules to ground, 0.75–3.0 lb active/acre.	Absorbed through the roots, poorly through foliage. Readily translocated in xylem. Mode of action: photosynthesis inhibitor.	Very persistent in soils, half-life of l2–l5 months. More persistent in dry soils and high organic matter soils. Poor mobility in soils.	Slightly toxic. Oral LD_{50} for rats is 644 mg/kg. Three generations feeding trials indicate no toxicity to rats.	Unrestricted. Grazing: Up to 20 lb product/acre, no withholding.	Higher doses, 15 lb product/acre or higher, can injure grasses.

Triclopyr

Garlon 3A®, amine salt (Dow AgroSciences)
Garlon 4®, ester (Dow AgroSciences)
Pathfinder II, ester, ready-to-use (Dow AgroSciences)
Redeem®, amine salt (Dow AgroSciences)
Remedy , ester (Dow AgroSciences)

Use	Application	Behavior in plants	Behavior in soil	Toxicity	Regulations
Controls broadleaves including woody plants in pastures and natural areas. Christmasberry, downy rosemyrtle, Formosan koa, gorse, guava, strawberry guava, highbush blackberry, Java plum, melastoma, night-blooming cereus, thimbleberry, velvet tree, yellow Himalayan raspberry sensitive. Downy rosemyrtle, lantana, Madagascar ragwort tolerant of foliar applications. Many woody species sensitive to cut-surface or basal bark applications including lantana, kiawe, downy rosemyrtle.	Foliar spray, basal bark (ester) and cut-surface.	Readily absorbed by foliage and roots. Translocates in the phloem. Mode of action: hormonal.	Mobile in soils. Degraded by microorganisms and sunlight. Average half life: 10–46 days.	Low order of toxicity. Acute oral LD_{50} for rats is 2l40 mg/kg.	Unrestricted. Grazing: For lactating animals on pastures treated with up to 2 lb/acre, 14 days withholding, for rates between 2–6 lb/acre, no grazing until the next growing season. For other livestock on pastures treated with up to 2 lb/acre, no withholding but remove three days before slaughter during year of application. On pastures treated with rates between 2–6 lb/acre, 14 days withholding and remove three days before slaughter during year of application. If less than 25% of the pasture is treated, no grazing restriction.

Appendix 2. Common and Botanical Names of Weeds Mentioned in the Text

Listed here are the botanical names of weeds of Hawaii mentioned in this publication. For additional information on these weeds, see Wagner et al.(110), Neal(81), and Haselwood et al.(41). Color photographs of some of these weeds may be found in Pratt(91) or Whistler(115). Color photos and management notes may be found in Lorenzi and Jeffery(63), Motooka et al.(78), and in the forthcoming CTAHR publication, *Weeds of pastures and natural areas of Hawaii and their management*, by Motooka et al., in preparation.

Common name	***Botanical name***
ageratum, tropic	*Ageratum conyzoides*
apple-of-Sodom	*Solanum linnaeanum*
ardesia, shoebutton	*Ardesia elliptica*
banyan, Chinese	*Ficus microcarpa*
blackberry, highbush	*Rubus argutus*
black wattle	*Acacia mearnsii*
bur bush	*Triumfetta rhomboidea*
cactus, prickly pear	*Opuntia ficus-indica*
Californiagrass	*Brachiaria mutica*
catsclaw	*Caesalpinia decapetala*
christmasberry	*Schinus terebinthifolius*
downy rosemyrtle	*Rhodomyrtus tomentosa*
elephantsfoot, false	*Elephantopus spicatus*
emex, spiny	*Emex spinosa*
faya tree	*Myrica faya*
Formosan koa	*Acacia confusa*
fountaingrass	*Pennisetum setaceum*
ginger, kahili	*Hedychium gardnerianum*
ginger, white	*Hedychium coronarium*
ginger, yellow	*Hedychium flavescens*
gorse	*Ulex europaeus*
guava	*Psidium guajava*
guava, strawberry	*Psidium cattleianum*
guineagrass	*Panicum maximum*
hamakua pamakani	*Ageratina riparia*
hilahila	*Mimosa pudica*
huehue haole	*Passiflora suberosa*
java plum	*Syzygium cumini*
Job's tears	*Coix lacharyma-jobi*
joee	*Stachytarpheta dichotoma*
kamole	*Polygonum glabrum*
karakanut	*Corynocarpus laevigatus*
kiawe	*Prosopis pallida*
koa haole	*Leucaena leucocephala*
lantana	*Lantana camara*
Madagascar ragwort (fireweed)	*Senecio madagascariensis*
Maui pamakani	*Ageratina adenophora*
Mauritius hemp	*Furcraea foetida*
melastoma	*Melastoma candidum*
molucca albizia	*Paraserianthes falcataria*
morningglory, Indian	*Ipomea indica*
nightblooming cereus	*Hylocereus undatus*
palmgrass	*Setaria palmifolia*
paperbark	*Melaleuca quinquenerva*
pluchea, Indian	*Pluchea indica*
ragweed parthenium	*Parthenium hysterophorus*
raspberry, yellow Himalayan	*Rubus ellipticus*
roseapple	*Syzygium jambos*
Sacramento bur	*Triumfetta semitriloba*
sourbush	*Pluchea carolinensis*
thimbleberry	*Rubus rosaefolius*
turkeyberry	*Solanum torvum*
velvet tree	*Miconia calvescens*

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