Chapter 8
Targeted and Microdose Chemical Applications

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Abstract In cropping systems, the precise application of herbicides is important for efficacious weed control. By using plant recognition and precision application technology targeting individual plants, off-target movement can be eliminated and herbicide rates significantly reduced without sacrificing yields. Highly targeted applications of nonselective herbicides into a growing sensitive crop are novel operations, nonexistent before the development of plant-specific targeting. New application technologies are essential when spatial rather than chemical selectively is to be deployed. In many potential applications, the chemical delivery system becomes the spatial resolution and speed limiting factor in the system.

1 Introduction

Weeds compete with crops for resources, including light, soil moisture, and nutrients. Significant yield reductions are associated with excessive weed growth and have been reported for all major crops (e.g., Donald and Khan 1992; Fischer and Ramirez 1993; Hall et al. 1992; Pike et al. 1990). Weed growth can be reduced with cultivation and cultural activities, including planting date, variety selection,

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and cover crops in certain situations. The judicious use of herbicides is also an effective method for reducing weeds and, in the past half century, has been the primary tool in most crops grown on small to very large acreages. Lower efficacy is often associated with inadequate herbicide rates, development of resistance, improperly timed applications, or treatments that partially or completely miss the target. A repeat herbicide application is typically lower in efficacy, is expensive, and can have long-lasting effects on the weeds (e.g., weed resistance) and the environment (e.g., surface and ground water contamination).

Precision treatment of weeds utilizes ultralow doses of herbicides that are applied directly to the target at a very early life stage. By applying herbicides early in the life cycle of weeds, efficacy and crop yields can be improved significantly. Giles et al. (2004a) report 85–100 % control of pigweed species (*Amaranthus albus* L., *A. blitoides* S. Wats.), black nightshade (*Solanumnigrum* L.), and spotted spurge (*Chamaesyce maculata* (L.) Small) in newly planted tomato (*Solanum lycopersicum*) using a microdosing jet that delivered 37-uL per spray cell (0.63 × 1.25 cm). Similarly, Sogaard and Lund (2007) demonstrate a microdose system with a potential for controlling up to 100 weed seedlings m^{-2} using only 4 g ha^{-1}(12 ml ha^{-1}) of glyphosate. For 90 % control of yellow foxtail (*Setaria pumila* (Poir.) Roemer & J.A. Schultes) and velvetleaf plants, a direct application of glyphosate, using a mechanical end effector, required 22 % of the active ingredient (145 g aiL^{-1}) in a broadcast application (Hong and Tian 2009). Precisely placed herbicides can be very effective in controlling weeds without resulting in lower crop yields (Felton and McCloy 1992), but the commercial availability of precision application equipment is limited by its robustness in a wide variety of field conditions, including fluctuating weather and changing plant canopy and architecture (Moody et al. 2004). In addition, targeted recognition and application technology for precision weed control must be easily incorporated into current systems or used as standalone implements (Deng et al. 2010; Søgaard and Lund 2007).

Over the past decade, rapid advancements in automation and real-time recognition have occurred for weed control in cropping systems (see reviews by Singh et al. 2011; Slaughter et al. 2008a). The use of sensors and computers to quickly assess plants and their location within a field has led to the development of various systems. For example, a vision-based system was developed for broadleaf dock (*Rumex obtusifolius* L.) in grasslands using 2-D Fourier analysis to classify images (van Evert et al. 2009). Algorithms from the classified images successfully detected broadleaf dock in each image sequence covering an area of 1.5 m^2 every 30 milliseconds. In lettuce (*Lactuca sativa* L.), Slaughter et al. (2008b) used visible and near infrared reflectance spectroscopy to distinguish leaf and head lettuce varieties from weed foliage. Using equipment mounted on a mobile platform, 90 % crop vs. weed classification accuracy was obtained on over 7,000 individual spectra representing 150 plants. A machine vision-based detection system was used by Nieuwenhuizen et al. (2010) in sugar beet (*Beta vulgaris*) to identify and control volunteer potatoes (*Solanum tuberosum*) and had almost 80 % accuracy with very low crop death (1 %). The trend for improving plant recognition technology and incorporating it with other management applications (e.g., yield, soil nutrients, moisture) is increasing at a pace that is similar to the development of other high-end technology systems. For example, Zijlstra et al. (2011) describe technologically advanced devises, such as electronic noses that detect volatiles released by pathogens, acoustic detectors for identifying insects, and portable PCR units for real-time identification of fungal, bacterial, and viral diseases, as the future for monitoring pests in a comprehensive program for managing cropping systems.

While several research- and a few commercial-grade systems are being developed for targeted applications, little is known about the precise rates of herbicides that are needed to control very small weed seedlings. Similarly, little is known about the tolerance and recovery of crop plants when exposed to near proximal “micro-drift” rates of herbicide. Studies have been conducted on reduced doses and spray volumes (e.g., Schumacher and Hatterman-Valenti 2007), but not at the microscale. Dose-response relationships have been used most often for herbicide efficacy (e.g., Al-Khatib et al. 1995) and more recently for detecting herbicide-resistant weeds (e.g., Riar et al. 2011) and other less common weed control tools, such as flaming (Sivesind et al. 2009), clove oil (Boyd and Brennan 2006), and mustard seed meal (Boydston et al. 2011). More research is needed to evaluate the response of individual weed species to micro-rates and the efficacy of the equipment used for making targeted applications.

Similarly, little is known about the tolerance and recovery of crop plants when exposed to near proximal “micro-drift” rates of herbicide. Giles et al. (2004a) reported that “splash”-induced (i.e., “micro-drift”) phytotoxicity experienced by the crop plants due to the micro-treatment reduced crop yield greater than weed competition from untreated weeds. The finding illustrated the potential for improperly executed micro-treatments to have a greater adverse effect than nontreatment of weeds. However, the work also identified the importance and usefulness of proper formulation, including physical property altering spray liquid adjuvants of the applied microdose treatments.

2 Efficacy of Chemical Weed Control

Weeds that have been injured by herbicides in the early growth stages (e.g., 2-leaf stage) are not likely to compete and survive in a field with a well-established and vigorously growing crop (Zimdahl 2004). Leaf sizes of weeds vary and can have a significant effect on herbicide coverage, which suggests that targeted applications can be tailored to meet specific individual plant sizes. What is true for broadcast applications of herbicides in identifying the precise plant growth stage that results in the most efficient and effective weed control treatment also applies to microdose herbicide applications made directly to plant surfaces.

The growth and development of weeds have been documented for many cropping systems (Buhler et al. 1998; Evans et al. 2003; Hall et al. 1992; Schier 2006; Wagner and Robinson 2006), showing the importance of implementing timely management strategies (see Chap. 4). A short period (e.g., 3–4 days) is sometimes all that is needed for plants to progress from cotyledon stage to the 2-leaf stage, demonstrating the ability of plants to quickly mature and thus the necessity for constant monitoring.

Glyphosate, a nonselective herbicide, is commonly applied to control annual weeds in cropping systems. In the field, a postemergence application at a typical field rate (1.6 L ha^{-1}) will kill many plants up to a certain growth stage. At this same rate, more mature plants are only injured and quickly recover. Early in the growth of a newly germinating plant, the surface of cotyledon leaves can vary from bare to very pubescent or hairy. As plants mature, the supple and malleable surface of seedling leaves increases in epicuticular wax content and becomes more resistant to absorbing liquids, such as herbicides and surfactants (Sanyal et al. 2006). Although the change in leaf surface texture is gradual in most weed species, it can play a role in limiting absorption and conductance of liquids across membranes (see Wang et al. 2007; Wang and Liu 2007). Therefore, the early stages of many weed species are the periods at which the leaf surface may be most likely to absorb an herbicide application, particularly at microdose concentrations.

In addition to texture, the role of leaf angle is a factor in limiting absorption and conductance of liquids across the leaf surface. The downward tilting of some weed species could be a response to the environment (e.g., sun, wind, rain) or an evolutionary response either to competition for light through a more aerodynamic and upright growth trajectory or a diversion of precipitation to the base of the plant (see Weinig 2000). For some weed species, the downward tilt of leaves makes it more difficult to get sufficient herbicide absorbed into the plant to cause death.

The traditional approach to making postemergence herbicide applications is through numerous nozzles spaced evenly along a boom that moves over the crop canopy. This method of applying herbicides emits an excessive amount of materials into the environment (e.g., off-target) where the target weed is located. The additional amount of materials can be easily quantified for comparison to microherbicide application rates. A 109 g $aeha^{-1}$ rate (1/8th of a typical field rate) of glyphosate in a microdose volume of 20 μl that is applied directly to the leaf surface of a velvetleaf weed in cotyledon-leaf stage requires 9.7 μg ae cm^{-2} to achieve over 90 % control (Young, unpublished data). The same rate of glyphosate applied in a typical spray volume of 187 Lha^{-1} would emit enough material to completely cover over 20 ha in a single layer of droplets (187 × 109 = 20,383 g ae = 20,383,000,000 μg ae/9.7 μg ae cm^{-2} = 2,101,340,206 cm^{-2} = 21.01 ha). If the typical field rate were used (868 g $aeha^{-1}$), the area covered would quadruple twice to 168 ha (21.01 ha/0.125 or 1/8th of a typical field rate = 168 ha). Clearly, the excessive application of herbicides could be reduced with more targeted and precise applications.

3 Equipment for Chemical Weed Control

A fundamental performance demand for spatially selective, real-time treatment of weeds in close proximity with crop plants is the deposition of small volumes of spray liquid exclusively on the weed targets. This demand is a novel requirement, in contrast to conventional herbicide applications where the physical scale of target areas may be hectares. In spatially selective applications, within early season crops, the target areas may be on the scale of square millimeters, many orders of magnitude different from conventional, traditional herbicide application.

Achieving requisite, high spatial resolution of liquid deposit from a moving vehicle requires high-frequency, very brief emission times to reduce the minimum length of deposition along the axis of travel (i.e., the spatial resolution) and individual control of liquid emission sources to reduce the minimum width of deposition normal to the axis of travel (i.e., the spatial resolution). This demand for high-frequency delivery of small, repeatable volumetric doses to small spatial areas presents a unique design challenge. Typical agricultural nozzles are unsuited for this use due to their high flow rates and diverging spatial spray patterns. Because diverging fan spray patterns produce a spray width that is dependent on the distance from the nozzle to the target, variation in plant height or nozzle position above the plant would change the spatial resolution of the application. Additionally, the variation in droplet velocity across the sheet, when coupled with forward movement of the vehicle, alters the distribution of liquid deposit.

The demand for high temporal and spatial placement of a spray liquid (or any other weed control means) is a physical limitation. While sensing, detection, and navigation systems are continually being improved by advances in electronics and computer processing capabilities, physical placement and materials handling remain limited by physical actuators, positioners, and spray emitters. Physical systems are being improved, however, at a lower rate than electronic systems.

The current trend in design of the few microdosing systems that have been deployed in the field is to fabricate a liquid emitter source with a narrow treatment "footprint" that is the product of a physically narrowed width treated by an individual emitter and a rapid control means for actuating flow from the individual emitter. By creating a narrowly spaced array of individually controlled emitters and providing for high-speed on/off capability of each emitter, the "footprint" of each actuator, when in motion, is minimized, thereby creating high spatial resolution. In an example of this design, a common supply manifold is created to provide pressurized liquid to an array of high-speed solenoid valves that control the flow to individual "slices" of orifice plates (Fig. 8.1). The orifice plates create an array of cylindrical jets of spray liquid oriented vertically downward to the target area to be treated. The liquid jets provide a means to "spray" the target weeds while minimizing the deposition on nontarget crop plants. In this particular example, the manifold also provides the means for the liquid to be heated, allowing the potential for thermal treatment of weeds.

A typical pulsed-jet, microdosing system uses an array of circular jets oriented vertically downward. Circular jets have been theoretically and experimentally tested and found to be very efficient at retaining a high exit velocity for many diameters downstream. The width of the deposition area (dimension normal to the direction of travel) is determined by the number of individual jets joined into a distinctly controlled unit. The length of the deposition area (dimension along the direction of travel) is determined by the ground speed of the vehicle and the minimum pulse time of the jet array.

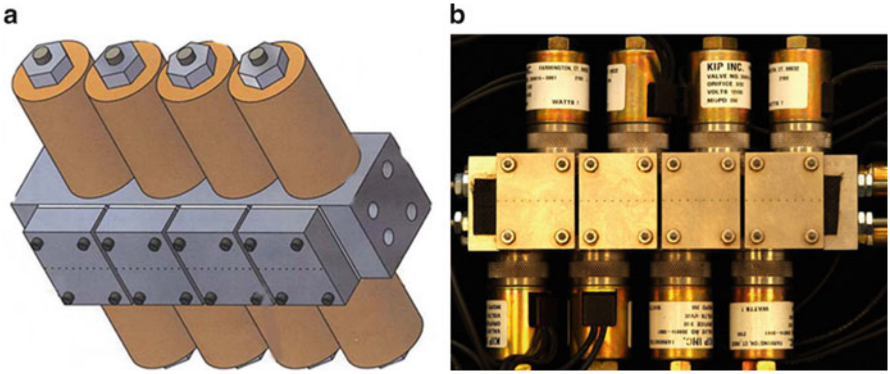

Fig. 8.1 Precision spray system for treatment of seedline weeds (Giles et al. 2004b). An engineering drawing rendered to show a manifold, control valves and orifice plates (**a**) A bottom view of the actual assembly showing the valves and the orifice blocks (**b**) (Photos courtesy of D.K. Giles)

The design criteria for a microdosing system is often established by the physical dimensions of the weed detection system with which it was intended to be used. For example, if displacement measurement along the direction of travel is a limiting factor, the resolution of the encoder for the ground wheel may be 0.65 cm (Lee et al. 1999). At a typical speed of 22 cm/s, which might be required for complex image analysis, the operating frequency (cell/s) will be 34 Hz with the frequency increasing proportionally with ground speed. In row crops, weed sensing systems can be limited to inspection and treatment of a narrow band (e.g., 10 cm along the crop row centerline). Outside of this band, weed control could be done by cultivation or continuous band spraying. Autoguidance systems, based on RTK GPS, may allow closer treatment, reducing the width of the band that must be inspected and spot treated. Lee et al. (1999) reported the development of a treatment system constructed as a linear array of type 304 W stainless steel hypodermic tubes, 1.25 cm long × 0.27 mm i.d. and inside chamfered on each end. Five tubes were placed 0.25 cm apart to create a linear array covering the 1.25 cm width. Eight, individually controlled arrays provided the 10 cm treatment width along the row centerline. Flow to each tube array was controlled by a direct-acting, DC solenoid valve with 12 V DC, 6 W coil, and 0.65 cm internal flow orifice. Minimum cycle time for the valve was measured as 6 ms; therefore, a minimum duty cycle of 20 % could be achieved at 34 Hz operation (Fig. 8.1).

An advantage of discriminating between plants to make spatially selective applications of herbicide to weeds is that nonselective herbicides can be used. This ability can reduce cost, improve chemical efficacy, and, when used in organic crop production, allow use of naturally derived, organic herbicides for weed control. However, inadvertent deposition of nonselective herbicide on the crop plant can result in significant phytotoxicity. This concern is important because the fundamental premise of a machine vision system is to allow weed control in the seed line, which is usually in close proximity to young crop plants that may be extremely sensitive to herbicide deposition. Often, the efficacy of foliar-applied herbicides is highly related to the uniformity of deposition and extent of leaf area covered by the spray deposit. Surfactants are commonly used with herbicide formulations to reduce surface tension and improve spread and uptake of the droplets after deposition. However, as surface tension is reduced, the potential for splatter and “splash” of the impacting high-energy jet increases. Even if the system was highly accurate at locating weeds and dispensing the liquid to exclusively strike the leaf surfaces of the weeds, the splash of the liquid stream could damage or kill the crop plants.

Giles et al. (2004a) and Downey et al. (2004) reported design and optimization of the fluid physical properties for use in highly resolved spatial treatment systems. The design demand was to engineer a fluid mixture that provided a high degree of target coverage and efficacy (consistent with a low surface tension and low viscosity) while preventing undesirable “splash” to target plants in close proximity to the target weeds (consistent with high viscosity and high surface tension). An optimal mix of surfactants and high molecular weight polymers was developed that provided an acceptable combination of efficacy and drift suppression.

Considering the future, as detection capabilities improve and the desire for higher vehicle speed increases, the demand for more highly resolved, both spatially and temporally, spray treatment systems will increase. Nonagricultural industries (e.g., high-speed printing, 3-D printing for fabrication) share the same design demand for improved spray actuators. It is likely that technologies developed for other demanding industries will be available for adaptation to this unique agricultural spraying need. Technologies such as piezoelectric actuators, ink-jet emissions, ultrasonic atomization, and robotic coating systems will offer potential solutions for agriculture.

An additional constraint, and perhaps a limiting factor beyond the technical concerns, is the regulatory status of allowing nonselective herbicides to be applied in fields with sensitive crop plants. Often a highly selective microdose application is made to a particular crop at a particular time in the season or in a particular location in a manner that is in conflict with the label instructions and chemical registration. Given that labels and regulatory registration data packages are developed and submitted by the chemical registrants with only traditional and conventional uses anticipated, the use of these chemicals in microdose, highly targeted applications may fall outside the intended use conditions. Therefore, the issue of legal status of the chemical use in these non-label applications will require resolution.

4 Conclusions

Precision application of weed control treatments requires sensitive technology that can track, record, and compute information on leaf shape, color, surface, and edge features for separating a weed and a crop plant (Hearn 2009; Meyer et al. 1998; Lati et al. 2011; Slaughter et al. 2008b; Tang et al. 2003; Tellaeche et al. 2011). The technology is still emerging and has a few challenges, including occluded leaves, misshapen leaves, moving leaves, and dusty leaves (see Chap. 15). Nevertheless, the algorithms to account for the changing plant and environmental conditions are being developed by engineers and computer scientists and will result in more accurate recognition and precision application systems (Zijlstra et al. 2011).

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