REDUCED HERBICIDE USAGE IN COTTON AND OTHER ROW CROPS USING OPTOELECTRONIC DETECTION

Jim Beck
Patchen California Inc.
Los Gatos, CA

Abstract

Chlorophyll bearing plant tissue has a very unique spectral reflectance in the visible and near infrared (NIR) wavelengths. Attempts to use reflected sunlight, passing through optical filters in an attempt to distinguish between plants and other objects has proven inconsistent at best.

Recently, equipment has been developed using an approach which provides discrimination equally well in bright sunlight, in shadows or in total darkness. It generates its own light from solid state light emitters which are modulated to isolate them from the sunlight. Problems associated with earlier attempts to accurately detect the presence of small amounts of plant tissue using spectral reflectance have thus been eliminated.

Background

Regulation of the use of herbicide materials is an ever increasing problem for farmers. Every year a longer list of material types are banned from use. One result of public pressure and regulation has been increased cost of herbicide materials. In most crops today the cost of herbicide and its application is a major component in the cost of production. The spraying of postemergence herbicide is one example where "selective application" to plant foliage can result in significant savings. This approach leads to the reduction of the use of soil-active chemicals. Additionally, the selective application of certain insecticides, fungicides and plant nutrients to plant surfaces can represent substantial cost savings and reduced environmental concerns.

In many typical farming operations, an early season application of preemergence chemical herbicide is used to discourage germination of weed seeds. During the growing season, postemergence herbicide is applied by traditional means to control weeds that escape the preemergence treatment. The amount of material which is used is far more than that required due to the primitive nature of the equipment being used. This technique has worked effectively over the past three decades but is unnecessarily expensive and raises serious questions about environmental issues. The time is quickly approaching when this wasteful practice will not be permitted at any cost.

Selectively spraying agricultural chemicals in a way that causes them to contact only foliage and not the bare ground or open air is not a new idea. Successful "selective application" of chemical materials, sometimes referred to as "spot spraying" or "intermittent spraying", has been limited in the past to a person visually observing the plant to be treated and then manually directing a spraying device. Devices which attempt to automatically sense plants, either mechanically or through the use of electrical conductivity, sonar, light or infrared radiation have not been widely accepted. Previous attempts, without exception, have had serious performance or cost disadvantages. Some examples include a weed sprayer which uses a horizontal light beam which is interrupted by weeds which are taller than the crop plants. The limited usefulness of this approach is obvious. Other examples include orchard sprayers which use sonar to detect the presence of trees then attempt to avoid spraying spaces between trees. Mixed results have been reported with the sonar device, indicating that maintenance and cost effectiveness are issues left to be improved upon.

There has been for generations, a strong interest in using reflected optical images to control agricultural equipment. There exists considerable prior-art in the United States, in Great Britain and in the USSR dating back as far as 1947. Few of these innovations have ever been reduced to practice because the technology required was not practical until recently.

At least one herbicide application device has become available which relies upon the unique spectral reflectance of living plant tissue to detect the presence of weeds. It uses optical filters and silicon photodetectors to separate two critical wavelengths, then compares the signals representing these wavelengths using electronic circuitry. The usefulness of this device is limited by the use of naturally occurring ambient light as the radiation source. Relying upon sunlight presents the difficulty that the sun's spectral distribution changes dramatically as the sun sweeps across the sky. Spectral variations as well as intensity variations are relatively unnoticeable to human eyes but have dramatic implications to analytical radiometric sensing devices. This sunlight based equipment is able to compensate somewhat for large shadows by directing a second photodetector pair to the sky as a differential reference. Additionally, the unpredictable effects of changing sun angle and cloud cover can be partially compensated for by continual operator adjustments. However, the lack of tolerance for localized shadows combined with a somewhat large (8" X 24" or 200 mm X 600mm) field-of-view and high detection threshold, make this equipment totally ineffective in perennial crops or under the canopy of row crops.

The WeedSeeker^{tm} Method

This method involves a family of products which operate on the principle that growing plants have a characteristic

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:62-66(1997)
National Cotton Council, Memphis TN

spectral reflectance in the visible and near infrared spectrum which can be discriminated from the background of the earth. They identify the location of weeds and meter out the precise amount of herbicide needed to treat weeds on an individual basis.

This equipment focuses on minimizing or eliminating preemergence herbicide materials. Preemergence chemicals are more expensive and are often looked upon as being hazardous to the environment because of their persistence of activity in the soil. Some postemergence materials, on the other hand, are extremely friendly in terms of environmental impact, and other materials which are not even classified as herbicides are effective weed control agents when combined with WeedSeeker^{tm} technology.

Employing the new method, the early season preemergence treatment is done with a fraction of the herbicide used in the current method or eliminated entirely. The selective and precisely targeted application of postemergence herbicide is much more effective later in the growing season.

Since the use of this equipment does not require the operator to physically view the area being sprayed, and since the equipment generates the necessary light required for weed detection, 24 hour operation is possible. Spraying herbicide at night offers some significant advantages. Cooler night temperatures allow longer and more efficient working hours at critical times during the growing season. The absence of sun prolongs effectiveness of the herbicide material. The higher relative humidity at night aids foliage wetting and the absence of wind after sunset in many areas minimizes over-spray. All of these things result in greatly enhanced efficiency in the use of the herbicide material.

Technology

It is well known that chlorophyll bearing plant tissue has a very unique spectral reflectance in the upper visible wavelengths and in the near infrared (NIR). Figure 1 shows reflectance comparisons between typical growing plant tissue, dead leaves, mineral soil and a certain parasitic weed. Comparing the reflected energy in the near infrared (NIR) to that reflected in the chlorophyll absorption band (approximately 670 nm) makes the plant tissue color signature unique. Earlier inventions attempted to use reflected sunlight, passing through optical filters to separate these two wavelengths in an attempt to distinguish between these objects. Spectral variations and shadows from trees, buildings or in fact the spray vehicle itself render a device using sunlight inconsistent at best.

The technology recently developed specifically for this application uses an approach which allows the device to work equally well in bright sunlight, in shadows or in total darkness. The WeedSeeker^{tm} generates its own light from solid state light emitters which are RF modulated. The detector circuitry is tuned to the modulation frequency which has the effect of isolating this light from the sunlight.

High efficiency and precise wavelength Gallium Aluminum Arsenide light emitters are focused precisely in a narrow band on the ground, under the sprayer and perpendicular to the vehicle direction of travel. They are powered by an internal power source and modulated under the control of a microcomputer which is also contained within the module. These devices have sufficient bandwidth to allow modulation frequencies in excess of 1 MHz. Phase shift and frequency modulation techniques have pronounced advantages in this type of application since virtually all potentially interfering noise sources are predominantly amplitude varying. The sun has no coherent phase or frequency noise which could interfere. Since discriminating between chlorophyll bearing plant tissue and all other objects can be done with only two wavelengths a bi-phase modulation technique is very effective. The demodulation can be done using a quadrature detector of the type used in FM radio since the phase angle of the current in the detector is directly proportional to the ratio of the two wavelengths being detected. Applications requiring three or more wavelengths as a means of discriminating between plant species or making absolute identification of certain objects use the familiar synchronized emitter-detector-pair technique or tone coding/decoding.

The modulated optical and infrared energy is selectively reflected back to the module in a ratio which is dependent upon the presence of chlorophyll bearing foliage in the field of view. Silicon PIN photodetectors are mounted in the module; precisely aligned behind an optical system which efficiently shapes and captures the light energy.

To enhance the equipment's ability to detect cotyledon size weeds, the field-of-view (FOV) of the system is constrained in both axes. In the axis perpendicular to the direction of vehicle travel, the reflected beam is masked by an aperture having a shape and physical placement which allows a constant beam width to strike the detector independent of height variations above the ground. Since naturally occurring ambient light is ignored by the system, the detector image is confined by the width of the reflected modulated light beam in the direction of vehicle travel. Constraining the shape of the reflected image being allowed to strike the detector provides more than an order of magnitude improvement in the size of weeds being detected as compared to previous sunlight systems.

The detectors and associated demodulation circuitry convert the photo energy into low level analog currents which contain the color signature of the objects in the field-of-view. Demodulation and analog to digital conversion is used to make the information compatible with the internal computer.

Each module contains its own microcomputer which takes into account the color signature of the objects in the field-of-view along with information about the background lighting and the speed of the vehicle. Software stored in an Erasable Programmable Read Only Memory (EPROM) allows the computer to make a decision about the disposition of an object in the field of view and command the sprayer heads to take the appropriate action. When the computer decides that a weed is present, one or more of the selectively controlled spray heads emits a short burst of herbicide directly onto the foliage and specifically avoids spraying the surrounding area.

This design approach has eliminated the problems associated with earlier attempts to accurately detect the presence of small amounts of plant tissue using spectral reflectance.

It was not possible until recent years to bring the various elements described above together in a cost effective way. The Gallium Aluminum Arsenide epitaxy has recently been pioneered for traffic lights and automobile tail lights; the valves used in the spray heads have been recently developed for ink jet printers; lower cost microcomputers and memory make it possible to integrate these things at affordable costs. Of similar importance has been that cost and regulatory pressure are now demanding a more efficient solution and the technology is evolving to fill that need.

Products

The first of these new products, introduced in 1992, was an eight channel device having nozzles and detectors with two inch spacing. It was directed primarily toward weed control in vineyards. This product has been replaced by a single nozzle product introduced in 1995 having a spray pattern width which is programmed before leaving the factory. Individual modules can be mounted as close as three inches (75mm), or as much as twelve inches (300mm) apart, which allows them to be customized for specific applications. This device addresses the use of chemical herbicide in row crops as well as vineyards, orchards, small grain farming and rights-of-way,. Figure 2 shows the underside of an individual single nozzle unit mounted in a row-crop spray hood. Near the top of the photo, the unit is seen to have a circular detector lens, measuring approximately one inch (25mm) in diameter. Immediately below is a cylindrical lens which shapes the modulated light beam. Below that are the electrical cables which connect each unit to the controller. Finally in the lower portion of the photo is the solenoid valve cartridge and associated plumbing parts. This equipment has demonstrated that it is able to conserve herbicide material and application costs that return the capital investment in much less than one year in large cotton plantings. In most cases the annual cost of weed control has been reduced by a minimum of 50% and often as much as 70%.

Applications

Perennial Crops

Figure 5 shows a typical vineyard configuration. Vineyard weed control tends to be very intensive, focusing on the smallest of weeds. This is true because the canopy usually does not totally obscure the ground under the vine row from the sunlight and because even a relatively low weed cover can have significant effect on crop yield and quality. Conversely, many orchards use strip widths which measure several feet on either side of the tree row. Being cost effective with these wider strips requires a lower cost solution, represented by Figure 6 where three single nozzle modules are able to cover a three foot (1meter) strip. These boom mounted configurations are also appropriate for roadsides, railroad rights-of-way and other non-agricultural applications, simply by adding more sprayer modules to cover wider strips.

Row Crops

In cotton and other row crop applications, these modules are mounted under hoods which protect the crop from over-spray. Many row crops tend to develop a dense canopy early enough in the growing season such that only larger weed patches are of concern. When several rows are sprayed simultaneously, the equipment investment required suggests a field-of-view and spray pattern of 12" (300 mm) or more, such as that shown in Figure 7.

Because of these varying requirements, a wide range of products with different spray patterns are appropriate. With the above considerations taken into account, the model shown in Figure 4 allows the observer to compare weed sizes (w) to spray pattern sizes (s) and predict a certain saving potential for each combination. The 2” (50 mm) rectangular weeds in this example can be replaced with weeds of any size and shape. In addition, experience indicates that weed formations generally tend not to be random but rather are found in patches, being influenced by wind, rain, seed availability, etc.. This reality would tend to make the potential for savings greater than that indicated by Figure 4. The dashed line in Figure 4 represents a summary of several large field trials conducted during 1996 in cotton and soy beans in California and the Delta. Average savings over several thousand acres sprayed in 1996 amounted to approximately 70% over the conventional hooded sprayer method.

In cotton and certain other row crops, plant spacing within the row is often uneven and the canopies of adjacent plants tend to grow into each other or conversely there are occasional gaps in the rows where no plants exist. In such situations, it is desirable to discriminate between weeds and crop plants to enable weeds to be selectively sprayed while avoiding the crop. When a cotton plant is less than a few weeks old, its stalk is soft green tissue which is somewhat translucent to near infrared light. The stalk also reflects strongly in the infrared and it appears to have much the same spectral reflectance as a weed might have. It is therefore difficult to discriminate the cotton crop from the weeds. At a later stage, the stalks become woody and decrease in similarity to weeds in terms of spectral reflectance. The stalks can therefore be discriminated from the weeds.

The traditional method for weed control within the rows would be to spray at the base of the plants (post-directed spray) with a continuous band of selective chemical herbicide (MSMA) which can be tolerated by the crop. The WeedSeeker^{tm} ability to discriminate cotton stalks from weeds after the stalks have taken on their woody appearance opens up the possibility to do post-directed, in-the-row, selective spraying. Recent experience indicates that a major impact can be realized in the amount of herbicide required for optimum weed control using this technique

Estimating Herbicide Savings

It would be tempting to estimate a certain percentage of weed cover in any crop setting and relate that percentage directly to the amount of spray which could be saved using certain "selective spraying" technologies. It becomes apparent however that the relationship cannot be quantified without considering several related parameters.

The field of view (FOV) of a particular detector should closely approximate the size of the spray pattern (s). It would not be prudent for the detector to "see" a particular area on the ground and for the spray pattern to be either smaller or larger than the area being examined by the optical system. In one case, weeds could be detected but the spray pattern would not be able to hit them, resulting in inadequate weed control. In the other case, an inappropriately large spray pattern would waste material by spraying outside of the field-of-view (FOV). Beyond this first observation, other considerations are less obvious. Some parameters to be considered include:

Individual weed size (w)
        (w_1) = weed length in the direction of travel
        (w_2) = weed width perpendicular to travel
    Detector Field-of-View (FOV)
        (d_1); in the direction of travel
        (d_2); perpendicular to the direction of travel
    Spray pattern (s)
        (s_1); in the direction of travel
        (s_2); perpendicular the direction of travel
    Detection threshold (D_{th}) measured in % (FOV)
        (minimum detectable weed area)
    Weed cover (WC) measured in % field
    Spray ratio (SR) measured in % field sprayed

Figure 3 shows a page from a computer model developed for the purpose of exploring the relationship between the above parameters. It represents a section of a field with variable weed content. All dimensional parameters can be varied to simulate any given weed situation. The user is able to sketch a particular weed pattern on the computer screen using a mouse and observe the effect on spray material saving with various spray patterns. Using the model it is possible to alter critical parameters such as nozzle type, (s_1) and (s_2); and Detection threshold (D_{th}), then interactively compare various selective spraying approaches.

Figure 4 shows a sample result derived from the computer model. It is made up of a family of curves showing the relationship between weed cover (WC) and spray ratio (SR). It assumes that all weeds are rectangular and measure two inches on each side. It is strictly theoretical and conservative to the extent that it assumes that weeds are randomly scattered. Clearly, as the size of the spray pattern of each nozzle of a selective spray system decreases with respect to the weed size, the potential for saving increases. When the spray pattern is much smaller than the nominal weed size, the total area sprayed will approximate the actual weed cover. At the other extreme, where the spray pattern is much larger than individual weeds, more material is wasted than actually comes in contact with the weeds. There is a task-appropriate field-of-view (FOV), spray pattern (s) and Detection threshold (D_{th}) for every application and it is possible that the correct combination for a given weed/crop situation may not be effective for another.

The detection threshold (D_{th}) is a variable of considerable importance. It sets the limit to which the system is able to discriminate between plant tissue and background. There are system limits imposed which relate to the noise-floor, bandwidth and distortion properties of the optical and electronic systems. Given that these are held constant, the detection threshold (D_{th}) is a function of two primary ratios. The first is the relative difference in reflectance at the two subject wavelengths. The other being the ratio of weed area to non-weed area in the field of view. The first ratio is optimized by choosing the most advantageous wavelengths of energy to be reflected. This is done by choosing one wavelength at the peak of the chlorophyll absorption band and the other at a convenient place in the near infrared (NIR) where reflectance is relatively higher. The area ratio issue is addressed with an optical system design discussed earlier which has two primary goals. The first is a fixed field-of-view width (d_2) irrespective of the distance from detector to object. The other is a very small and fixed field-of-view length (d_1). As field-of-view length (d_1) approaches zero the area ratio (w_1 x w_2) : (d_1 x d_2) ceases to be a square law function and approaches the linear (w_2 : d_2). This allows much smaller weeds to be detected than might otherwise be possible. This choice requires that the system bandwidth be proportionally increased as the (d_1) value is decreased, due to the fact that more samples of reflectance data must be taken and processed per unit time.

The current state of this technology makes possible the detection of 1/8" (3 mm) diameter weeds using a field of view of 2" X 3/16" (50 mm x 5 mm). Widening the 2" dimension tends to degrade the detectable weed width proportionally in linear fashion. It is not affected in relation to the weed area because the field of view is constrained as described above.

It should be noted that the minimum possible D_{th} may not be appropriate for every application. It is often advisable to spray only weeds of a certain size and allow the crop canopy to crowd-out the smaller ones. A wide variation of weed distributions and crop characteristics suggest many different field-of-view and spray pattern variations. In addition, the device is equipped with a sensitivity control which allows the operator to program the system to ignore weeds under a certain size.

Future Products Using Optoelectronic Technology

The potential for the technology described herein goes far beyond the selective application of herbicide. Following are examples of future applications of derivative technologies.

Generically Specific Sprayers

There is reason to believe that future products using spectral reflectance will differentiate between plant species based upon their unique spectral reflectance characteristics. Figure 1 shows substantial differences between the reflectance of common chlorophyll bearing plant tissue and the parasitic weed. Less pronounced but substantial differences exist between various other plant species. In the future, these differences will make it possible for "selective sprayers" to identify certain crops and non-crop plants and treat them individually with applications of herbicides and other pesticides or nutrients.

Vehicle/Implement Guidance

Row-crop farming puts significant demands on operators of farm equipment. Whether accomplishing cultivating, spraying or other row specific farm operations, guiding the vehicle and/or implement accurately, as close to the rows as possible, at speeds as high as possible, without damaging the crop poses a constant series of tradeoffs.

The technology described here holds interesting potential for this application. Several detectors are able to determine that an object has entered the field of view and indicate whether the object is a living plant. The computer examines the output of each detector periodically and stores the information in solid state memory. The information is "mapped" to represent a visual impression of the location and physical properties of objects in the vicinity of the vehicle or implement. The computer compares the current data being gathered from the detectors to the data stored in memory. From the information available, the computer is able to make very accurate predictions based upon plant sizes and locations and plot a line which represents the centerline of the crop row, then guides the vehicle or implement accordingly.

Chemical-Free Weed Control

Equipment for chemical-free weed control and thinning in row crops is possible which will employ an optical sensing technique to determine the exact location of the foliage. When weeds or improperly spaced crop plants are detected the computer instructs a mechanical hoe to remove them leaving the desired crop plants undisturbed. This equipment eliminates costly hand labor and uses no chemical herbicide. Similar chemical-free field-crop weed removal equipment will likely be developed which relies upon the spectral reflectance differences of the foliage, along with other dimensional parameters and discriminates certain weed species from crop plants. In addition to the mechanical removal of weeds, considerable interest exists in integrating this sensing technology with currently available flame cultivation equipment as well as with high power lasers.

Summary

A new technology has been described which addresses a need which has existed since the advent of agricultural chemicals. It brings elements of modern optoelectronic technology to bear on one of the most important problems facing agriculture today - maintaining profitability in the face of ever increasing costs and government regulation of the use of agrochemicals.

Equipment is now available which provides discrimination between chlorophyll bearing plant tissue and most other objects, equally well in bright sunlight, in shadows or in total darkness. It generates its own light from solid state light emitters which are modulated to isolate them from the sunlight. Problems associated with earlier attempts to accurately detect the presence of small amounts of plant tissue using spectral reflectance in sunlight have thus been eliminated.

We should expect to see significant advances in this area of technology development over the next several years. These advances will lead to dramatic reductions in the amount of agricultural chemicals used in the United States and around the world.

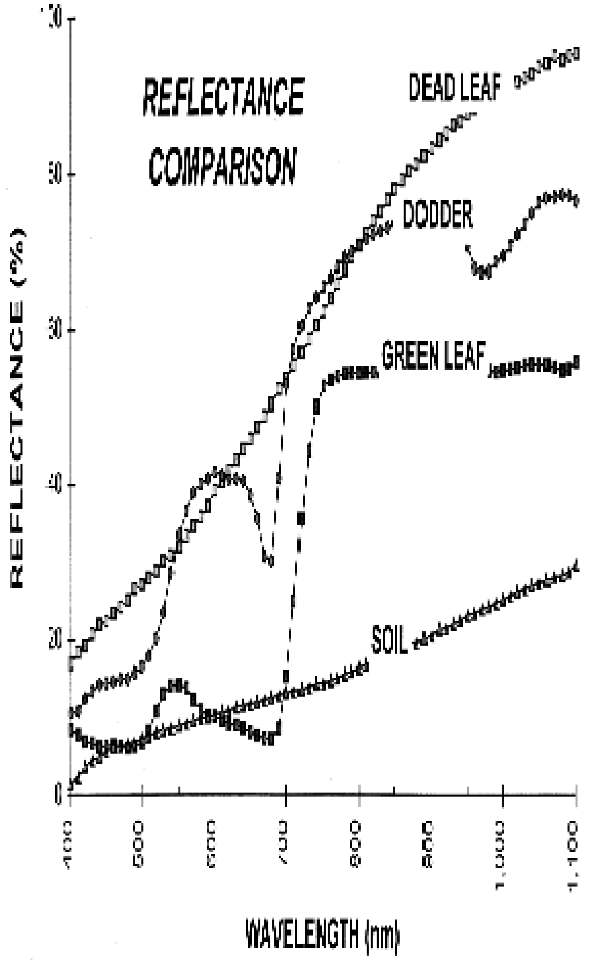
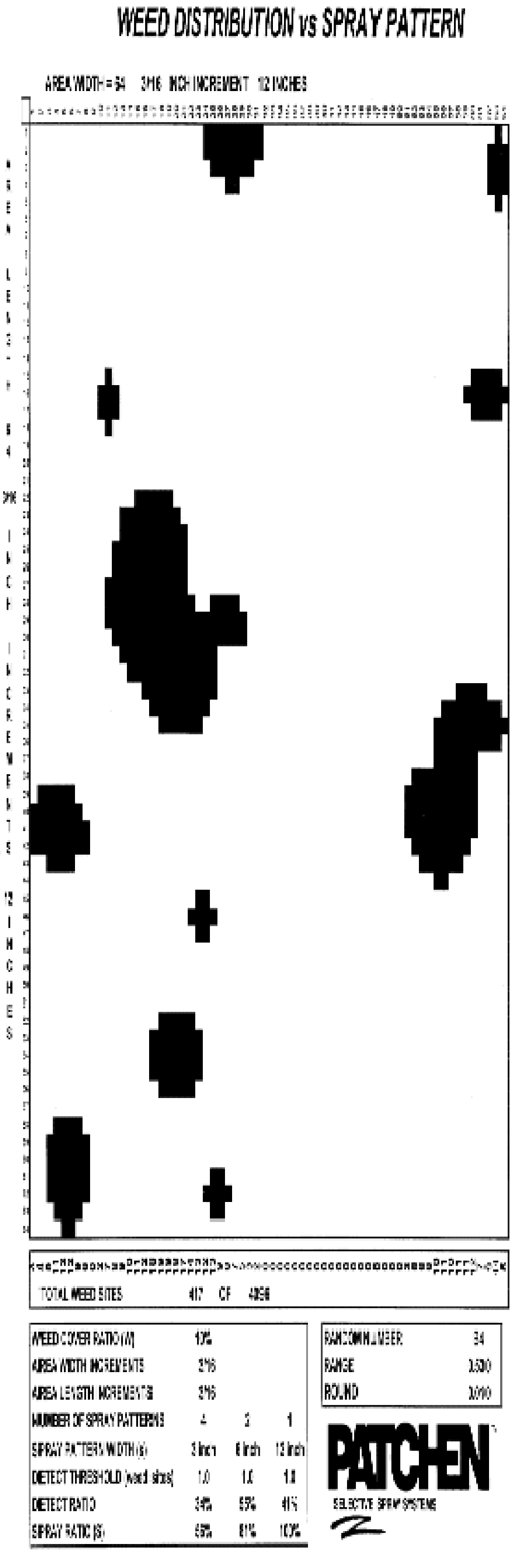


Figure 1

Figure 2



WEED COVER RATIO (W)	10%		
AREA WIDTH INCREMENTS	3/16		
AREA LENGTH INCREMENTS	3/16		
NUMBER OF SPRAY PATTERNS	4	2	1
SPRAY PATTERN WIDTH (s)	3 Inch	6 Inch	12 Inch
DETECT THRESHOLD (weed sites)	1.0	1.0	1.0
DETECT RATIO	34%	55%	41%
SPRAY RATIO (S)	65%	81%	100%

RANDOM NUMBER	34
RANGE	0.500
ROUND	0.090

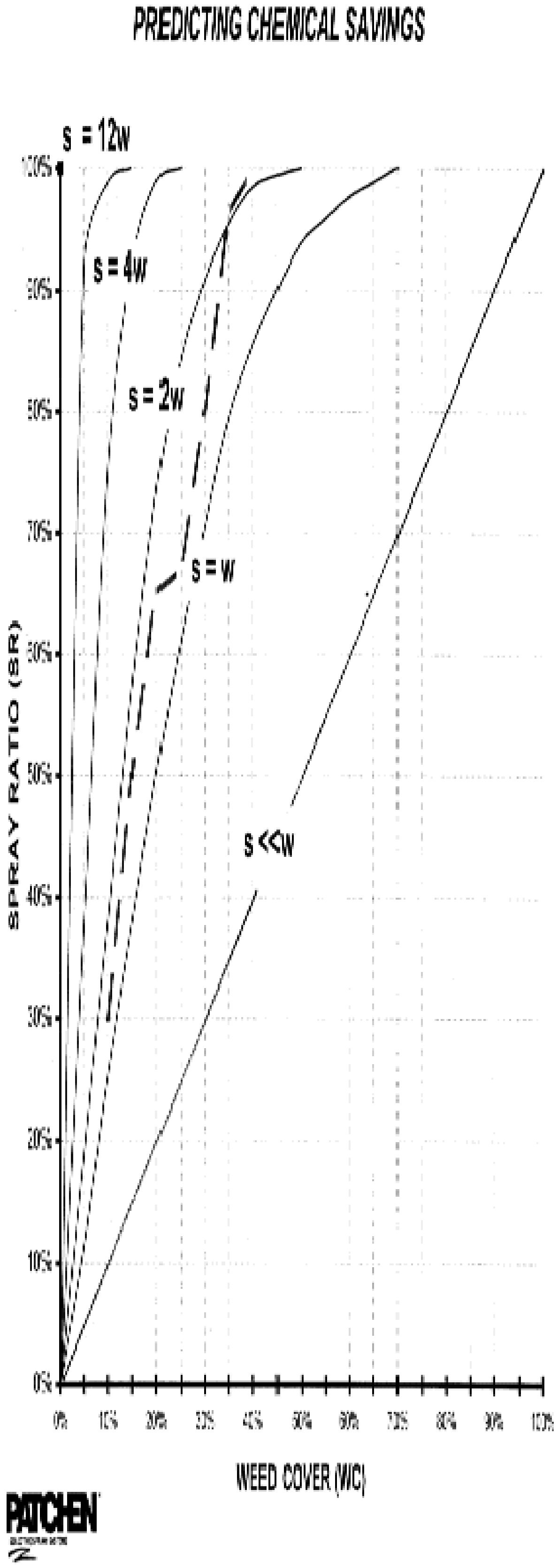


Figure 4

Figure 3


Figure 5


Figure 6


Figure 7