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Review

HADSS™, Pocket HERB™, and WebHADSS™: Decision Aids for Field Crops[1]

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Abstract: Row crop weed management decisions can be complex due to the number of available herbicide treatment options, the multispecies nature of weed infestations within fields, and the effect of soil characteristics and soil-moisture conditions on herbicide efficacy. To assist weed managers in evaluating alternative strategies and tactics, three computer programs have been developed for corn, cotton, peanut, and soybean. The programs, called HADSS™ (Herbicide Application Decision Support System), Pocket HERB™, and WebHADSS™, utilize field-specific information to estimate yield loss that may occur if no control methods are used, to eliminate herbicide treatments that are inappropriate for the specified conditions, and to calculate expected yield loss after treatment and expected net return for each available herbicide treatment. Each program has a unique interactive interface that provides recommendations to three distinct kinds of usage: desktop usage (HADSS), internet usage (WebHADSS), and on-site usage (Pocket HERB). Using WeedEd™, an editing program, cooperators in several southern U.S. states have created different versions of HADSS, WebHADSS, and Pocket HERB that are tailored to conditions and weed management systems in their locations.

Nomenclature: Corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; peanut, *Arachis hypogea* L; soybean, *Glycine max* L.

Additional index words: Bioeconomic models, computer decision aids, decision support systems, weed management.

Abbreviations: HADSS, Herbicide Application Decision Support System; PDS, postemergence-directed; POST, postemergence; PPI, preplant-incorporated; PRE, preemergence.

INTRODUCTION

Many factors are considered when selecting an appropriate weed control strategy within a cropping system for a given field. Decisions are complicated by the number of herbicide treatments available for crops such as corn, cotton, peanut, and soybean. Herbicide decisions are further complicated by the multispecies nature of weed complexes within fields, and substantial differences in herbicide efficacies due to weed species, weed size, soil characteristics, and soil moisture conditions. Availability of herbicide-resistant crop cultivars and associated technology fees or higher seed costs further complicate economics of weed management decision-making.

Standard weed control strategy for many row crops such as corn, cotton, soybean, and peanut has been to apply a preplant-incorporated (PPI) or preemergence (PRE) herbicide treatment (or both) to prevent weed germination, followed by remedial, postemergence (POST) or POST-directed spray (PDS) treatments to control weeds emerging after the crop (Hagood et al. 2001; Jordan and York 2002; York and Culpepper 2000, 2002). The introduction of herbicide-resistant varieties in crops such as corn, cotton, and soybean and the availability of many broad-spectrum, highly effective POST and PDS herbicides has made possible weed control strategies that rely less on PRE or PPI herbicides (Askew and Wilcut 1999; Bradley et al. 2000; Hart et al. 1997; Miller et al. 1999). One advantage of a total POST weed management approach is that more information about the nature and severity of the weed infestation is available at the time of herbicide treatment selection. Thus, herbicides with high efficacies for the emerged weed complex can be applied and the likelihood of successful weed control increased. However, a remedial-only approach is not without risk due to the number of POST or PDS herbi-

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cide choices available for most row crop production systems as well as the unpredictable nature of weather. In the event that the selected herbicide or preselected herbicide-resistant crop technology (i.e., glyphosate application in a glyphosate-resistant crop) is ineffective against the emerged weed complex, or inclement weather prevents timely application for early season weed control, yield loss may occur (Askew and Wilcut 1999; Buchanan and Burns 1970; Clewis et al. 2000; Culpepper and York 1998; Scott et al. 2001).

During the past 20 yr, many decision models have been developed to assist growers and other weed managers in weed control decision-making for several crops. These decision aids have generally fallen into one of two categories (Mortensen and Coble 1991): those that make recommendations primarily on the basis of herbicide efficacy (Linker et al. 1990; Renner and Black 1991; Stigliana and Resina 1993; Thomson and Williamson 1992) and those that consider weed seed bank or weed seedling density and make a recommendation based on economic benefit (Berti and Zanin 1997; Krishnan et al. 2001; Lybecker et al. 1991; Mortensen et al. 1999; Pannell 1990; Swinton and King 1994; Wiles et al. 1996; Wilkerson et al. 1991). HERB™, a decision model for postemergence weed control in soybean, is an example of the latter category and is the predecessor of the HADSS family of decision aids (Wilkerson et al. 1991).

Rapid changes in both weed control and computer technologies during the past 10 yr have necessitated and facilitated development of new decision aids with greater capabilities. A weed management decision aid that is not regularly updated to incorporate new information and to take advantage of computer hardware and software advances will rapidly become obsolete. Since HERB was first introduced, the availability of herbicide-resistant crops technology has had a major impact on weed management in several crops. Handheld computers are now available with more computing power than that of the best desktop machines 10 years ago. Internet use increased from 13% of all farms in the United States in 1997 to 43% in 2001 (Economic Research Service 2001).

In a recent review of weed management decision models, Wilkerson et al. (2002) discussed many of the challenges facing model developers, as well as possibilities for utilizing current computer technology to provide situation-specific weed management decision-making assistance in a timely fashion. With increasing Internet accessibility, more and more information is being distributed to extension personnel and their clientele in this manner. Pl@ntInfo, a web-based decision support system developed by the Danish Institute of Agricultural Sciences and the Danish Agricultural Advisory Centre to provide decision support to farmers and their advisors, was launched in 1996 (Jensen et al. 2000). Handheld computers provide a mechanism for making decision models available in the field at the time a decision is needed. Desktop computer systems have become so powerful and sophisticated that many of the constraints that limited HERB and other early decision models no longer apply.

HERB, an MS-DOS[3]–based program, was designed for use by a single user on a desktop computer. It was supplied on diskette. In 1998, in cooperation with scientists at the University of Georgia, HERB was modified so that it could run on MS-DOS–based handheld computers (Murphy et al. 1998). These computers could be carried into the field, allowing users to enter scouting information and obtain a recommendation while in the field. Also, cooperators in Georgia set up a web site from which HERB could be downloaded for installation on a desktop or handheld computer. In all, HERB was updated nine times before its final release in 1999. When it became clear that HERB's useful lifespan was drawing to a close due to advances in technology, we decided to retain the functionality of HERB but develop several related programs to address different users' needs. Whereas HERB could run on both desktop and handheld computers without problems, developing a new program to run on both desktop and handheld systems was not feasible, given differences in operating systems, software availability, and screen size and resolution of these computers.

Developing computer decision aids is an expensive undertaking, making it impractical and inefficient for weed scientists in each state to develop programs independently. However, weed problems and management strategies differ from location to location, so that a decision aid developed for one state often may not be used without some modification in another. Soon after HERB was first released, we began cooperating with weed scientists at several locations to develop versions adapted to conditions in their area. It became clear that developing a method for easily modifying program databases would be essential if these cooperative efforts were to continue.

The creation of the HADSS family of decision aids

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(HADSS,[4] Pocket HERB, and WebHADSS[5]) was undertaken with the goal of utilizing current computer technologies to better assist growers, extension personnel, consultants, and others involved in weed management in making timely, effective, and economically sound weed control decisions. Our objectives were to develop a decision support system that (1) would allow weed managers to compare weed management strategies in terms of efficacy, cost, and expected economic returns, (2) would assist weed managers in evaluating conditions within fields and provide on-site treatment information, (3) could be used in classroom and extension settings to demonstrate the complexity of weed management decisions and associated risks and benefits of alternative approaches, (4) would be available and useful to a broad range of weed managers with varying needs for weed management assistance, and (5) could be adapted to many cropping systems and updated as needed to reflect changes in weed management options.

MATERIALS AND METHODS

Like HERB (Wilkerson et al. 1991), the three decision aids in the HADSS family use information on weed biology, herbicide efficacy and cost stored in the software, and field-specific information supplied by the user to rank treatments on the basis of expected net return. However, the three programs have been designed to meet different needs, as described below. HERB has been described elsewhere (Wilkerson et al. 1991), but we include a brief description of its main features in order to make clear both the similarities and differences among these programs.

HERB. In HERB, the competitive ability of each weed species is characterized using a competitive index (Coble 1986). This index represents the degree of competitiveness the weed species has with the crop; it ranges from 0 to 10, with 10 assigned to the most competitive weeds. Competitive index values have been developed from weed competition studies when available and from expert opinions of cooperating weed scientists. An estimate of total competitive load is calculated by multiplying weed density per unit ground area by this competitive index and summing across species (Coble and Mortensen 1992; Wilkerson et al. 1991). For each treatment, a predicted total competitive load value after control is calculated on the basis of initial weed densities and expected treatment efficacy. A linear relationship between total competitive load and percent yield loss is assumed at low weed densities, and a hyperbolic relationship is assumed as density increases.

Herbicide efficacy depends upon weed species, average weed size, and soil moisture conditions (Bruce et al. 1996; Olson et al. 2000; Wie et al. 1997). Weed size is divided into three height categories: $<$ 5 cm, 5 to 10 cm, and $>$ 10 cm. Soil moisture is divided into two categories: adequate and dry. Adequate is defined in this model as allowing active plant growth, while dry conditions would be those that do not sustain active growth. Each treatment has six efficacy values for each weed species, one for each weed size–soil moisture condition combination. The herbicides, tank mixtures, and corresponding application rates included in program databases are those deemed most appropriate for each weed size–soil moisture combination.

HERB uses expected crop selling price, herbicide prices, application costs, and expected weed-free yield (supplied by the user) to calculate expected net return for each treatment in the database. Treatments are ranked according to these expected net returns, and users can view information on expected yield loss, weed control, cost, and returns for each treatment.

HADSS. This is a desktop program, designed to provide a full spectrum of weed control recommendations including PPI, PRE, POST, and PDS treatments. It may also be used for preseason planning and for storing field weed management information to assist in herbicide resistance management. Although HADSS still provides recommendations on the basis of expected economic returns, it allows users to sort treatments by other criteria and provides more information than did HERB to assist in decision making.

HADSS calculates expected net returns for POST and PDS treatments as described above for HERB. For PPI and PRE treatments, herbicide efficacy depends upon weed species and soil characteristics (organic matter content and soil surface texture). Reduced bioavailability of many soil-applied herbicides due to soils containing increased organic matter and increased clay mineral content has been documented by many investigators (Loux et al. 1989; Obrigawitch et al. 1981; Shaw and Murphy 1997). Within HADSS, organic matter content is divided into three categories: $<$ 1%, 1 to 3%, and $>$ 3%. Surface texture is also divided into three categories: coarse (sand/sandy loam/loamy sand), medium (loam/silt/silt loam), and fine (clay/clay loam/sandy clay/sandy clay loam/silty clay/silty clay loam). These categories are in accord with

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[5] http://www.cropsci.ncsu.edu/webhadss/.

many PPI and PRE herbicide labels (Anonymous 2000, 2001a, 2001b). There are nine efficacy values for PPI and PRE treatments, one for each organic matter content–soil texture combination. Cooperating weed scientists have provided efficacy values on the basis of field experimental results and expert opinion when field data are lacking.

Information is organized by grower and field name in HADSS. The information required for a given field depends on the user's choice of application method. For PPI and PRE recommendations, the information required is crop, expected weed-free yield, crop selling price, estimated weed density on the basis of field history, field size (acreage), and soil surface organic matter content, and texture. Field size is used for calculating the amount of herbicide needed to treat the whole field. If the user selects only POST or PDS treatments, the information required is crop, expected weed-free yield, crop selling price, average weed size, soil moisture status, field size (acreage), and weed density counts per unit ground area for each weed species in the field. On the basis of an economic analysis of potential losses with different levels of scouting, we recommend that the user make weed density counts in 10 to 12 randomly selected locations per field (Krueger et al. 2000).

Depending upon the crop selected, additional information (crop height, number of true crop leaves, soil pH, planting date, and expected application date) may be required to eliminate inappropriate treatments. For example, a treatment that can only be applied POST within 25 d after planting will be eliminated if the number of days after planting (as calculated from planting date and expected application date) is greater than 25. HADSS is distributed with default prices for each herbicide, but users can modify herbicide selling prices and application costs. This allows users to enter values that reflect their local costs.

Herbicide-resistant cultivars represent an additional input dimension. If herbicide-resistant cultivars are available for the specified crop, the user can then choose whether or not to consider the associated herbicides in the decision-making process. For preseason planning in HADSS, a user can enter an extra seed cost or technology fee, if appropriate, for each herbicide-resistant variety. This cost will be subtracted from expected net return for each treatment containing the herbicide that can only be used in conjunction with the herbicide-resistant crop variety. After planting, the investment in herbicide-resistant cultivars has already been made and should not be considered part of the decision process.

HADSS displays predicted yield loss information if no control measures are taken. Yield losses are presented as percent weed-free yield, bushels, tons, or pounds lint per acre, and dollars per acre. The loss attributed to each weed species is displayed, along with the total loss due to all weeds. The herbicide recommendation screen shows summary information about all available treatments. Tank mixtures and sequential treatments are included where appropriate. Treatments are initially listed from most profitable to least profitable. Herbicide names, rates, costs, yield loss remaining after treatment, and expected net return are listed for each treatment. By selecting the appropriate column heading, the user can sort treatments by herbicide cost or by after-treatment yield loss. This approach facilitates identification of treatments that are least expensive or provide the best overall weed control, regardless of cost or net return.

HADSS has an additional option that allows users to sort treatments according to control of a specific weed species. When this option is selected, HADSS displays a column for each weed species in the field. Each column contains the predicted number of weeds remaining per unit ground area after treatment application. Selecting a species name at the top of a column causes treatments to be sorted from most to least effective for the selected species. This feature has been added to assist weed managers in managing problematic weed species, where net return and overall herbicide efficacy are of less importance than control of a particular species.

On the herbicide recommendation screen, HADSS has an option to show label information. If the user is connected to the Internet, selecting this option connects the user directly to a World Wide Web site that maintains official herbicide label information. HADSS provides detailed, treatment-specific information. This feature displays name and application rate for each herbicide included in the treatment, method of application (PPI, PRE, POST, or PDS if more than one method of application is selected), estimated net return, total application cost, number of each weed species present per unit area before and after treatment, and estimated yield loss from each weed species before and after treatment. This feature also provides information on amount of each herbicide needed for the specified field size, total number of units of each herbicide to purchase, and total cost of herbicide(s) needed to treat the specified field size.

HADSS prominently displays a wide array of treatment-, herbicide-, and weed-specific messages that may be important for the user to consider while deciding on an appropriate treatment. These messages address a range of possible situations. Examples include messages that indicate the need to control a particular weed species because seeds are poisonous, there is potential for crop injury from a treatment, or there are rotational or environmental restrictions associated with a herbicide.

When a herbicide treatment is selected by the user, information about the treatment is stored in the field history database. The program uses this treatment information in subsequent years to flag treatments that may promote weed herbicide resistance. A treatment being considered within the current year is identified as possibly promoting weed resistance if both the following criteria are met: (1) the treatment utilizes a mode of action that has been used in all of the past 3 yr and (2) each year, the treatment constituent with this mode of action had efficacy against the same weed species (i.e., the same mode of action has been used to control a particular species for the past 3 yr). If these criteria are met, the program notifies the user that continuing to use that mode of action could promote selection for weed resistance, and the user should consider selecting a herbicide with a different mode of action.

HADSS can be run under Windows 98®, Windows NT 4.0®, Windows 2000®, and Windows XP® operating systems. The program is written in Microsoft Visual Basic 6® and stores data in a Microsoft Access 2000® database.

Pocket HERB. This program is designed to function on handheld computers and offers the convenience of entering field conditions and receiving in-field assistance with herbicide treatment selection. Because it is designed for within-season, in-field use, it only makes recommendations for POST and PDS treatments. Like HADSS, it stores information by grower and field name. Input data requirements are identical to those for POST and PDS recommendations in HADSS. Pocket HERB displays the same information about treatments as does HADSS and allows treatments to be sorted by multiple criteria, but the small screen size limits the amount of information that can be displayed at any one time.

Field information can be transferred between Pocket HERB and HADSS. This feature allows editing of basic field information and herbicide prices on a desktop or laptop machine prior to field scouting with Pocket HERB. Given the small size of handheld computer screens and the use of a stylus for data entry, our objective has been to minimize the amount of information that must be entered into Pocket HERB while in the field. Once grower and field information have been entered into HADSS and transferred to Pocket HERB, only information about the identity and density of weed species remains to be entered when visiting the field. Scouting data can be transferred from Pocket HERB to HADSS for permanent storage.

Pocket HERB can be run on handheld computers using the Microsoft Pocket PC® operating system. Pocket HERB is written in Microsoft Visual Basic–embedded C++® and stores data in random access files and the system registry.

WebHADSS. This program runs on a web server and can be accessed by anyone with an Internet connection and a web browser. WebHADSS was designed primarily (1) for classroom and extension education, (2) for weed managers with a small number of fields to manage for whom installing a custom desktop program would be inefficient, (3) for users who lack access to a Windows-based computer (e.g., many of the extension agents in North Carolina), and (4) as an easily accessible introduction to the HADSS family of decision aids.

WebHADSS is a fully functioning decision aid that makes recommendations for POST and PDS treatments. The same POST and PDS database is used in both HADSS and WebHADSS, and identical routines are used by both programs to calculate losses and net returns. Given the intended user base for WebHADSS, no mechanism for users to store and recall field information was included in the program. Users do not have the option of modifying herbicide prices, although they must specify all other input information needed by HADSS for POST and PDS treatments. WebHADSS displays the same information as HADSS does about yield loss, net return, and cost for each treatment, as well as the same warning messages. Treatments are sorted by net return, and the program does not allow the information to be re-sorted. This lack of sorting capability is due to programming constraints and may be modified in future versions.

The user interface for WebHADSS is written in hypertext markup language, while the database engine and database are identical to those in HADSS. WebHADSS can be accessed at www.cropsci.ncsu.edu/webhadss.

Program Structure. Each decision aid consists of two separate parts: (1) a user interface that collects input information and displays results, and (2) a library of routines that access database information and perform calculations. This design allows new applications with different user interfaces to be created utilizing already developed databases and algorithms. For example, a

Microsoft[6] Excel® spreadsheet has been developed that accesses HADSS databases and algorithms through Microsoft Visual Basic for Applications® to demonstrate principles of site-specific weed management in the classroom (Bennett et al. 1999).

Updating Program Databases. A key feature in developing, maintaining, and customizing decision aids is the ability of weed scientists to modify the underlying database. An editing program, WeedED, has been developed to allow cooperators to modify the database that HADSS, Pocket HERB, and WebHADSS share, including yield loss equation parameters; listed weed species; weed competitive indices; herbicide names, rates, modes of action, and cost; herbicide warning messages and use restrictions; single ingredient, sequential, and tank mix treatments; and treatment efficacies under different conditions. Cooperating weed scientists can make modifications to meet the conditions and expectations of weed managers, whether this involves modifying efficacy values, adding local environmental warnings, or including comprehensive information on rotational restrictions. Currently, only English-language versions are supported, but either metric or English units of measurement can be specified. Once weed scientists have constructed a database for use in a particular set of crops in a given geographic area, WeedED creates the databases that are used by all the decision aids. This allows cooperators to enter information only one time for use in all three programs.

Validation. The overall approach used in these decision aids to estimate yield loss from a multispecies weed population was validated using data from 76 separate soybean trials in North Carolina (Coble and Mortensen 1992) and from trials specifically designed to test algorithms for peanut (White and Coble 1997). The quality of recommendations generated by these programs and their precursor, HERB, has been evaluated in a number of field studies (Bennett et al. 2001; MacDonald et al. 1998; Monks et al. 1995; Rankins et al. 1998; Scott et al. 2001, 2002; Shaw et al. 1998). In general, these studies have shown that these programs in most cases can provide recommendations equivalent to those of an expert and weed control, yield, and net returns that are equal to or better than a grower's standard treatment. Program modifications to more accurately represent local conditions have improved overall results (Monks et al. 1995; Rankins et al. 1998).

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RESULTS AND DISCUSSION

Using WeedED, cooperators in Ontario, Canada, and several U.S. states have created, or extensively modified, versions of HADSS, WebHADSS, and Pocket HERB for corn, cotton, peanut, and soybean. At present, databases have been developed, validated, and made available for peanut, soybean, corn, and cotton in North Carolina; for soybean, peanut, and cotton in Georgia; for soybean in Mississippi; for cotton and peanut in Oklahoma; and for soybean and corn in Ontario, Canada (Weaver 1999). Versions for various crops in other locations may become available over time.

We have been somewhat surprised at just how different the state databases are. For example, in a recent comparison of the North Carolina and Oklahoma cotton databases, the following differences were found: 35 weed species in the North Carolina database are not included in the Oklahoma database; 14 species in the Oklahoma database are not in the North Carolina database; competitive indices differ between states for 22 of the species that are common to both databases; and herbicide treatments differ greatly between the two databases, leading to $<$ 1% commonality in treatment efficacy values (Price et al. 2002).

North Carolina extension agents who have used Pocket HERB generally like having the ability to enter scouting data and get recommendations while in the field. Agents involved in a project using Pocket HERB in the summer of 2002 suggested that a more extensive hands-on training session would be helpful. They found the training session that included running through only one actual example insufficient. Most agents had not used a handheld computer previously and encountered some problems related to general operation of the computer (e.g., forgetting to recharge batteries and losing the program from memory, having the program ''vanish'' from the screen and not knowing how to get it back, and losing the stylus). In the future we plan to expand the hands-on part of training sessions for new users substantially, covering other programs that are available on the computer as well as having users make several trial runs of Pocket HERB.

WebHADSS has been well received by users. Only the North Carolina and Ontario versions have been available long enough to develop a user base. Between April 2001, when the North Carolina and Ontario, Canada, versions were first made available, and July 2002, over 1,400 runs have been made (all required information was entered by the user and a recommendation requested). Of these runs, 42% were for soybean, 40% for corn, 13%

for peanut, and 5% for cotton. The relatively low usage for cotton is probably because cotton was only included in April 2002, and its availability has not been publicized. Usage patterns over time have generally followed the planting and weed management patterns for the crops. Most (72%) of the Ontario WebHADSS usage occurred between May 1 and July 15 each year. Peanut and soybean usage in North Carolina was largely (88% and 65%, respectively) between May 1 and July 31. However, only 45% of the North Carolina corn runs occurred between March 10 and July 10.

We have found that WebHADSS eliminates some of the problems we had using HERB in the classroom. Computers in university laboratories generally have access to the Internet, making it easy for classes to use WebHADSS. Getting custom software such as HERB or HADSS installed on university teaching laboratory computers for use in a particular class can be time-consuming or difficult to accomplish, depending upon computer configurations and university policies. At North Carolina State University, for example, such requests must be made several months in advance.

Development of these decision aids has been, and will continue to be, an evolutionary process. As we add additional cooperators and users, and as weed control technologies change, modifications are being suggested to improve the functionality and operation of the programs for particular users. Given the positive response of cooperators and weed managers to WebHADSS, we plan to include more functionality in this program as time and programming tools allow. As a web-based application, user technical support requirements are much lower for this program than for either HADSS or Pocket HERB. We are able to include links to other information sources that might be useful in weed identification or in decision making. We are also able to update databases whenever necessary, and the latest version is immediately available to all users. For instance, when a herbicide selling price was reduced substantially several weeks after the 2002 version of these programs was released, we were able to change the price immediately in WebHADSS. Pocket HERB and HADSS users had to be notified to change this price themselves.

In our interactions with weed scientists, growers, extension agents, and consultants during the development and implementation process, we have heard concerns related to using the HADSS family of decision aids. One concern is that weed managers do not or cannot expend the time required to scout fields for weeds in the manner recommended for the programs. The most common method of quantifying field weed populations for use in decision models has been to use weed density per unit ground area (Berti and Zanin 1994; Black and Dyson 1993; Martin et al. 2001; Wiles et al. 1996; Wilkerson et al. 1991) and is the approach recommended for use with the HADSS family of programs. However, other methods are available, such as grouping weed species into broad categories or entering density information as ranges (King et al. 1986; Lybecker et al. 1991; Mortensen et al. 1999; Wilkerson et al. 1999). Developing cost-effective and less time-consuming methods for quantifying weed populations remains an active area for research and may lead to improvements in future versions of the HADSS program family (Gold et al. 1996; Krueger et al. 2000; Murdock and Murray 2002; Wiles et al. 1992).

Another concern is correctly estimating weed populations prior to emergence for PPI and PRE recommendations. Clearly, estimating weed species densities prior to weed emergence is subject to uncertainty; however, it is necessary for direct comparisons of potential economic returns for PPI, PRE, and POST strategies. A user's uncertainty about weed population estimates prior to weed emergence may highlight the benefits of a remedial weed management strategy that relies upon field scouting. By changing estimated densities for each weed species, a user can see the impact of these changes on program recommendations and determine how dependent economic gain from a particular PPI or PRE treatment is upon weed densities. This information should help a user to decide whether a PPI or PRE application is appropriate for a particular field or a total POST strategy is most economically appropriate.

Another concern is the validity of economic thresholds. While economic thresholds have been validated within many crops, many growers have their own threshold that initiates treatment on the basis of personal philosophy. Also, growers consider other factors when making weed control decisions that are not included within the model, such as simplicity, use in multiple fields, relationships with chemical manufacturers or distributors, and effectiveness of the weed management systems in terms other than potential economic returns. We have tried to address these concerns by supplying as much information as feasible, by allowing the user to sort recommendations according to multiple criteria and by emphasizing that these programs are decision aids, not independent decision makers. Given the many uncertainties involved in making weed control decisions early in the season, we recommend that weed managers consider any recommendations with net returns within 10% of the top recommendation to be equally good.

HADSS, Pocket HERB, and WebHADSS offer many potential benefits to weed managers who make herbicide treatment decisions. They offer an easy way to examine potential economic benefits of a wide range of weed management treatments, something that can be extremely time-consuming otherwise. Weed managers can examine herbicides in terms of overall efficacy against the range of weed species found in fields, also a potential time-consuming process by any other method. The inclusion of appropriate and timely warning messages can provide weed managers with a range of information weed scientists think important, including environmental restrictions, rotational crop restrictions, and crop injury concerns. Much of the information can be obtained from other sources, but the structure of the decision aids brings a wide range of data relevant to the decision-making process together in a convenient, easy-to-access format.

HADSS, Pocket HERB, and WebHADSS can all be of value as educational tools. Weed managers may explore the effect of misidentifying weed species, underestimating or overestimating weed populations, delaying herbicide applications, applying herbicides under unfavorable conditions, or applying inappropriate herbicides. These programs can also be used to investigate potential economic benefits of new crop cultivars that have been genetically engineered to be resistant to specific herbicides.

Decision aids of this type also provide a mechanism for weed scientists to store and organize information in an easily accessible format. The four-crop (corn, cotton, soybean, and peanut) version of HADSS for North Carolina, including the PPI and PRE information, currently contains over 75,000 nonzero efficacy values for more than 600 treatments containing one or more of 91 herbicides. Although data requirements to create a database for a new crop can be extensive, particularly if there is little herbicide overlap with crops already in the database, modifying a database to meet the needs of a new state has not proved to be a major obstacle for the weed scientists involved. Yearly updates to a completed database are also necessary.

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LITERATURE CITED

Anonymous. 2000a. Dual Magnum product label. Greensboro, NC: Syngenta Crop Protection. 40 p.

Anonymous. 2000b. Canopy product label. Wilmington, DE: EI du Pont Nemours. 16 p.

Anonymous. 2001. AAtrex product label. Greensboro, NC: Syngenta Crop Protection. 16 p.

Askew, S. D. and J. W. Wilcut. 1999. Cost and weed management with herbicide programs in glyphosate-resistant cotton (*Gossypium hirsutum*). Weed Technol. 13:308–313.

Bennett, A. C., G. G. Wilkerson, and M. C. Sturgill. 2001. Validating a decision support system for the southern US. Weed Sci. Soc. Am. Abst. 41:134–135.

Bennett, A. C., G. G. Wilkerson, M. C. Sturgill, and D. W. Krueger. 1999. Using NCSU HADSS to teach site specific weed management. *In* Agronomy Abstracts. Madison, WI: ASA. 357 p.

Berti, A. and G. Zanin. 1994. Density equivalent: a method for forecasting yield loss caused by mixed weed populations. Weeds Res. 34:327–332.

Berti, A. and G. Zanin. 1997. GESTINF: a decision model for post-emergence weed management in soybean (*Glycine max* (L.) Merr.). Crop Prot. 16: 109–116.

Black, I. D. and C. B. Dyson. 1993. An economic thresholds model for spraying herbicides in cereals. Weed Res. 33:279–290.

Bradley, P. R., W. G. Johnson, S. E. Hart, M. L. Buesinger, and R. E. Massey. 2000. Economics of weed management in glufosinate-resistant corn (*Zea mays* L.). Weed Technol. 14:495–501.

Bruce, J. A., J. Boyd, D. Penner, and J. J. Kells. 1996. Effect of growth stage and environment of foliar absorption, translocation, metabolism, and activity of nicosulfuron in quackgrass (*Elytrigia repens*). Weed Sci. 13: 447–454.

Buchanan, G. A. and E. R. Burns. 1970. Influence of weed competition in cotton. Weed Sci. 18:149–154.

Clewis, S. B., J. W. Wilcut, S. D. Askew, and J. D. Hinton. 2000. Weed management in strip tillage roundup ready (glyphosate-resistant) cotton. Beltwide Cotton Conf. 1:1476.

Coble, H. D. 1986. Development and implementation of economic thresholds for soybean. *In* R. E. Frisbie and P. L. Adkisson, eds. CIPM: Integrated Pest Management on Major Agricultural Systems. College Station, TX: Texas A & M University. pp. 295–307.

Coble, H. D. and D. A. Mortensen. 1992. The threshold concept and its application to weed science. Weed Technol. 6:191–195.

Culpepper, A. S. and A. C. York. 1998. Weed management in glyphosate-resistant cotton. J. Cotton Sci. 2:174–185.

Economic Research Service. 2001. Agricultural Outlook. Washington, DC: USDA, ERS AGO 286.

Gold, H. J., J. Bay, and G. G. Wilkerson. 1996. Scouting for weeds, based on the negative binomial distribution. Weed Sci. 44:504–510.

Hart, S. E., L. M. Wax, and A. G. Hager. 1997. Comparison of total post-emergence weed control programs in soybeans. J. Prod. Agric. 10:136–141.

Hagood, E. S., C. W. Swann, and H. P. Wilson. 2001. Chemical weed control in soybean. *In* 2000 Virginia Soybean Production Guide. Virginia Cooperative Extension Service publication. pp. 91–108.

Jensen, A. L., P. S. Boll, I. Thysen, and B. K. Pathak. 2000. Pl@nteInfo—a web-based system for personalised decision support in crop management. Comput. Electronics Agric. 25:271–293.

Jordan, D. L. and A. C. York. 2002. Weed management in peanuts. *In* 2002 Peanut Information. North Carolina Cooperative Extension Service publication AG-331. pp. 23–51.

King, R. P., D. W. Lybecker, E. E. Schweizer, and R. L. Zimdahl. 1986. Bioeconomic modeling to simulate weed control strategies for continuous corn (*Zea mays*). Weed Sci. 34:972–979.

Krishnan, G., D. A. Mortensen, A. R. Martin, L. B. Bills, A. Dieleman, and C. Nesser. 2001. WeedSOFT: a state of the art weed management decision support system. Weed Sci. Soc. Am. Abstr. 41:41–42.

Krueger, D. W., G. G. Wilkerson, H. D. Coble, and H. J. Gold. 2000. An economic analysis of binomial sampling for weed scouting. Weed Sci. 48:53–60.

Linker, H. M., A. C. York, and D. R. Wilhite Jr. 1990. WEEDS—a system for developing a computer-based herbicide recommendation program. Weed Technol. 4:380–385.

Loux, M. M., R. A. Liebl, and F. W. Slife. 1989. Availability and persistence of imazaquin, imazethapyr, and clomazone in soil. Weed Sci. 37:259–267.

Lybecker, D. W., E. E. Schweizer, and R. P. King. 1991. Weed management decisions based on bioeconomic modeling. Weed Sci. 39:124–129.

MacDonald, G. E., D. C. Bridges, and B. J. Brecke. 1998. Validation of HERB computer decision aid for peanuts. Proc. South. Weed Sci. Soc. 51:216.

Martin, A. R., D. A. Mortensen, and L. Bills. 2001. Computerized weed management decision aids. Weed Sci. Soc. Am. Abstr. 41:114–115.

Miller, D. K., C. F. Wilson, and J. L. Milligan. 1999. Total postemergence weed control in roundup ready cotton with combinations of roundup ultra and staple. Proc. South. Weed Sci. Soc. 52:238–239.

Monks, C. D., D. C. Bridges, J. W. Woodruff, T. R. Murphy, and D. J. Berry. 1995. Expert system evaluation and implementation for soybean (*Glycine max*) weed management. Weed Technol. 535–540.

Mortensen, D. A. and H. D. Coble. 1991. Two approaches to weed control decision-aid software. Weed Technol. 5:445–452.

Mortensen, D. A., A. R. Martin, F. W. Roeth, et al. 1999. WeedSOFT Version 4.0 User's Manual. Lincoln, NE: Department of Agronomy, University of Nebraska.

Murdock, S. W. and D. S. Murray. 2002. Obtaining weed populations for computerized decision support system (DSS) inputs: counts vs. estimations. Proc. South. Weed Sci. Soc. 55:130.

Murphy, T. R., D. C. Bridges, G. MacDonald, B. J. Brecke, G. G. Wilkerson, and H. Coble. 1998. HERB User's Guide for Soybeans and Peanuts. Griffin, GA: The Georgia Station, Crop and Soil Sciences Department, The University of Georgia.

Obrigawitch, T., F. M. Hons, J. R. Abernathy, and J. R. Gipson. 1981. Adsorption, desorption, and mobility of metolachlor in soils. Weed Sci. 29: 332–336.

Olson, B.L.S, K. Al-Khatib, P. Stahlman, and P. J. Isakson. 2000. Efficacy and metabolism of MON 37500 in *Triticum aestivum* and weedy grass species as affected by temperature and soil moisture. Weed Sci. 48:541–548.

Pannell, D. J. 1990. An economic response model of herbicide application for weed control. Aust. J. Agric. Econ. 34:223–241.

Price, A. J., A. C. Bennett, and G. G. Wilkerson. 2002. HADSS validation and evolution of regional HADSS programs. Abstr. Weed Sci. Soc. Am. 42:55–56.

Rankins, A., Jr., D. R. Shaw, and J. D. Byrd. 1998. HERB and MSU-HERB field validation for soybean (*Glycine max*) weed control in Mississippi. Weed Technol. 12:88–96.

Renner, K. A. and J. R. Black. 1991. SOYHERB–a computer program for soybean herbicide decision making. Agron. J. 83:921–925.

Scott, G. H., S. D. Askew, A. C. Bennett, and J. W. Wilcut. 2001. Economic evaluation of HADSS™ computer program for weed management in nontransgenic and transgenic *Gossypium hirsutum*. Weed Sci. 49:549–557.

Scott, G. H., S. D. Askew, J. W. Wilcut, and A. C. Bennett. 2002. Economic evaluation of HADSS computer program in North Carolina *Arachis hypogaea*. Weed Sci. 50:91–100.

Shaw, D. R. and G. P. Murphy. 1997. Field persistence of bioavailable flumetsulam. Weed Sci. 45:568–572.

Shaw, D. R., A. Rankins Jr., J. T. Ruscoe, and J. D. Byrd. 1998. Field validation of weed control recommendations from HERB and SWC herbicide recommendation models. Weed Technol. 12:78–87.

Stigliana, L. and C. Resina. 1993. SELOMA: expert system for weed management in herbicide-intensive crops. Weed Technol. 7:550–559.

Swinton, S. M. and R. P. King. 1994. A bioeconomic model for weed management in corn and soybean. Agric. Syst. 44:313–335.

Thomson, A. J. and D. R. Williamson. 1992. Formation and use of intermediate inferences in advisory systems: a herbicide example. AI Applic. 6: 29–37.

Weaver, S., M. C. Sturgill, G. G. Wilkerson, H. D. Coble, and G. S. Buol. 1999. HADSS User's Manual, Ontario Version 2.0. Harrow, ON Canada: Agriculture and Agri-Food Canada. 24 p.

White, A. D. and H. D. Coble. 1997. Validation of HERB for use in peanut (*Arachis hypogaea*). Weed 11:573–579.

Wie, H. S., A. I. Hsiao, and W. A. Quick. 1997. Influence of drought on graminicide phytotoxicity in wild oat. (*Avena fatua*) grown under different temperature and humidity conditions. J. Plant Growth Regul. 16:233–237.

Wiles, L. J., R. P. King, E. E. Schweizer, D. W. Lybecker, and S. M. Swinton. 1996. GWM: general weed management model. Agric. Syst. 50:355–376.

Wiles, L. J., G. G. Wilkerson, H. J. Gold, and H. D. Coble. 1992. Modeling weed distribution for improved postemergence control decisions. Weed Sci. 40:546–553.

Wilkerson, G. G., S. A. Modena, and H. D. Coble. 1991. HERB: decision model for postemergence weed control in soybean. Agron. J. 83:413–417.

Wilkerson, G. G., L. J. Wiles, and A. C. Bennett. 2002. Weed management decision models: pitfalls, perceptions, and possibilities of the economic threshold approach. Weed Sci. 50:411–424.

York, A. C. and A. S. Culpepper. 2000. Weed management. *In* 2000 North Carolina Corn Production Guide. North Carolina Cooperative Extension Service publication. pp. 69–111.

York, A. C. and A. S. Culpepper. 2002. Weed management in cotton. *In* 2002 cotton information. North Carolina Cooperative Extension Service publication AG-417. pp. 76–125.