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Evaluating the Potential for Site-Specific Herbicide Application in Soybean[1]

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Abstract: Field experiments were conducted on two North Carolina research stations in 1999, 2000, and 2001; on-farm in Lenoir, Wayne, and Wilson counties, NC, in 2002; and on-farm in Port Royal, VA, in 2000, 2001, and 2002 to evaluate possible gains from site-specific herbicide applications at these locations. Fields were scouted for weed populations using custom software on a handheld computer linked to a Global Positioning System. Scouts generated field-specific sampling grids and recorded weed density information for each grid cell. The decision aid HADSS™ (Herbicide Application Decision Support System) was used to estimate expected net return and yield loss remaining after treatment in each sample grid of every field under differing assumptions of weed size and soil moisture conditions, assuming the field was planted with either conventional or glyphosate-resistant (GR) soybean. The optimal whole-field treatment (that treatment with the highest expected net return summed across all grid cells within a field) resulted in average theoretical net returns of $79/ha (U.S. dollars) and $139/ha for conventional and GR soybean, respectively. When the most economical treatment for each grid cell was used in site-specific weed management, theoretical net returns increased by $13/ha (conventional) and $4.50/ha (GR), and expected yield loss after treatment was reduced by 10.5 and 4%, respectively, compared with the whole-field optimal treatment. When the most effective treatment for each grid cell was used in site-specific weed management, theoretical net returns decreased by $18/ha (conventional) and $4/ha (GR), and expected yield loss after treatment was reduced by 27 and 19%, respectively, compared with the whole-field optimal treatment. Site-specific herbicide applications could have reduced the volume of herbicides sprayed by as much as 70% in some situations but increased herbicide amounts in others. On average, the whole-field treatment was optimal in terms of net return for only 35% (conventional) and 57% (GR) of grid cells.

Nomenclature: Glyphosate; soybean, *Glycine max* L., 'Natto.'

Additional index words: Computer decision aids, economic threshold, integrated pest management, variable rate herbicide application.

Abbreviations: CEFS, Center for Environmental Farming Systems; GPS, Global Positioning System; GR, glyphosate resistant; HADSS, Herbicide Application Decision Support System; TNR, theoretical net return over herbicide investment; YL, yield loss remaining after treatment.

INTRODUCTION

Management of weeds is an essential component of any cropping system. According to national statistics, herbicides were applied to 99% of soybean hectarage in 2002 (USDA 2003a). In general, U.S. crop producers pay about the same amount for pesticides and fertilizers (USDA 2003b). Nevertheless, precision agriculture has, to date, focused primarily on variable rate application of fertilizer. Comparatively little attention has been paid to site-specific herbicide applications although ''spot spraying'' of crops has been an important pest management technique for decades. Numerous studies have shown that weed distribution is not uniform across a field; weeds tend to be clumped together in patches (Cousens and Woolcock 1997; Dieleman et al. 2000; Gonzalez-Andujar and Saavedra 2003; Mortensen et al. 1997).

Several studies have investigated using site-specific weed management to take advantage of the inherent patchiness of weed populations within agricultural fields. Several forms of site-specific management are possible.

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The simplest consists of intermittent herbicide application in which the herbicide applicator is turned off in areas with no weeds or in areas in which the weed population is below an economic treatment threshold. Rew et al. (1996) mapped five fields and determined that if herbicides were only applied to areas where weeds were detected and no buffer areas around weed patches were included, then herbicide use could be reduced from 34 to 97%. Johnson et al. (1995) constructed spatial maps based on extensive scouting data from 12 corn (*Zea mays* L.) and soybean fields. They concluded that herbicide use could be reduced substantially by use of weed maps in combination with an intermittent herbicide application system, particularly if an economic threshold, rather than a zero population density threshold, were used to determine areas of treatment. Gerhards et al. (1997) estimated that herbicide use could have been reduced 40 to 50% by intermittent spraying using an economic treatment threshold in two winter wheat (*Triticum aestivum* L.) fields. Goudy et al. (2001) observed in a corn–soybean rotation that site-specific weed management, using a treatment threshold of >1 weed shoot/m^2, reduced the area sprayed by as much as 26%. Luschei et al. (2001) conducted on-farm trials to validate gains from using site-specific weed management compared with a conventional system in dryland spring wheat production. Results showed that yield was unaffected by treatment strategy; however, higher net returns were realized at two of the four study sites because of the reduction in area treated. Only one weed species was scouted, and the treatment threshold was based on presence or absence of this weed. Jurado-Exposito et al. (2003) found that herbicide use could be reduced by 61% at one location but only by 1% at another, when an economic threshold was used to determine treatment areas in cultivated sunflower (*Helianthus annuus* L.). This large discrepancy likely illustrates the high variability of weed populations within and between fields and the variable cost of herbicides that are available to producers.

A more complex system of site-specific management involves varying the rate of one or more herbicide in response to weed species and density changes from one portion of the field to another. Medlin and Shaw (2000) compared whole-field and site-specific herbicide applications using MSU-HERB and Mississippi Herbicide Application Decision Support System (HADSS). Estimated net gains from treating four fields site specifically were $104.76/ha and $96.24/ha for nontransgenic and glyphosate-resistant (GR) soybean, respectively. Results indicated that the smaller the sampling (treatment) grid, the larger the estimated net returns from site-specific management. Jordan et al. (2003) found that site-specific weed management increased theoretical net returns by $21/ha on average in 52 North Carolina peanut (*Arachis hypogaea* L.) fields and increased returns over whole-field treatment by more than $100/ha in a small percentage of fields. Sampling costs and extra application costs for site-specific management were not included in estimated returns in either of these studies.

Potential monetary benefits from site-specific weed management are not always easily measured in terms of increased revenue to producers. Site-specific weed management allows growers to target individual weed species or weed complexes with herbicides that provide the highest efficacy. Thus, by increasing weed control using site-specific management, growers may reduce the number of weeds that reach reproductive maturity and in turn decrease soil seed banks. Analyses by Canner et al. (2002) indicate that weed seed production and crop yield loss bear very similar relationships to weed density. Yield loss remaining after treatment (YL) can thus serve as an indicator of potential differences in weed seed production, allowing treatments to be compared in terms of possible effect on the seed bank.

Most studies to date have concentrated on evaluating changes in herbicide amounts required or potential net returns from site-specific weed management, using either an economic threshold or a weed density threshold to determine treatments. Our objectives in this study were to (1) assess the potential for site-specific herbicide application in soybean by comparing two decision-making strategies: using the treatment with the highest expected net return or using the treatment with the highest expected yield and (2) determine whether limited random sampling scouting data (sufficient for arriving at a whole-field recommendation) can be used to identify fields that might benefit from site-specific weed management.

MATERIALS AND METHODS

Pocket WeedMap™. This custom program runs on a handheld computer using the Microsoft Windows CE® operating system. By connecting a Global Positioning System (GPS) to the handheld computer, a scout can record the location of each weed population estimate. The program is designed for sampling according to a grid pattern. It allows users to enter information about weed species and densities in a field that has been subdivided into grid cells for variable-rate herbicide applications. The size and orientation of the rectangular grid

Table 1. Description of soybean fields scouted between 1999 and 2002 in North Carolina and Virginia.[a]

Site	Scouting date	Grid size	Number of grid cells	Soil-applied or burndown herbicides
		m		
Caswell Research Farm, Kinston, NC	July 16, 1999	30.5 × 30.5	18	None
	June 20, 2000	18.3 × 61.0	44	None
	July 5, 2001	23.2 × 61.0	33	Pendimethalin + metribuzin + chlorimuron
CEFS, Goldsboro, NC	June 28, 1999	30.5 × 30.5	36	None
	June 21, 2000	18.3 × 61.0	24	None
	July 24, 2001	18.3 × 61.0	39	None
Port Royal, VA, full-season plots	June 29, 2000	18.3 × 61.0	30	None[b]
	June 14, 2001	18.3 × 61.0	30	None
	June 5, 2002	18.3 × 61.0	30	None
Port Royal, VA, double-crop plots	July 17, 2000	18.3 × 61.0	90	Paraquat
	July 18, 2001	18.3 × 61.0	90	Paraquat
Lenoir County, NC	June 18, 2002	18.3 × 61.0	42	None
Wayne County, NC	June 25, 2002	18.3 × 61.0	30	None
Wilson County, NC	July 2, 2002	18.3 × 61.0	39	Metribuzin + Chlorimuron

[a] Abbreviation: CEFS, Center for Environmental Farming Systems.

[b] Herbicide and other information related to the Cropping Systems Experiment, Camden Farm, Port Royal, VA, was provided by M. M. Alley (personal communication).

cells is user defined, based on field shape, spray equipment, and time constraints (the smaller the grid, the more the time required to scout the field). If GPS is enabled, the program will show the scout's location as he or she moves from one grid cell to another. The scout also specifies the size of the area used for estimating weed densities; for example, the scout might want to estimate numbers per 3 ft of row if the population is dense. The program converts these estimates to number per 9.3 m^2, as required by HADSS (Bennett et al. 2003). Scouting data from the handheld program can then be transferred to a laptop or desktop PC for analysis.

Field Experiments. To compare site-specific herbicide application with whole-field herbicide application, field experiments were conducted in several locations in the coastal plain of North Carolina and Virginia during 1999, 2000, 2001, and 2002. Trials were conducted at the Center for Environmental Farming Systems (CEFS) in Goldsboro, NC, and at the Caswell Research Farm in Kinston, NC, in 1999, 2000, and 2001, as well as on three private farms in Lenoir, Wayne, and Wilson counties in North Carolina in 2002. Full-season and double-crop soybean (after winter wheat) plots in the Cropping Systems Experiment, Camden Farm, Port Royal, VA, were scouted in 2000, 2001, and 2002 (Anderson-Cook et al. 2002; Jones et al. 2003). GR soybean varieties were planted at all locations, except for the Wilson County site, NC. The edible soybean variety 'Natto' was planted at the Wilson County site in 2002. Row spacing was 76 cm at CEFS, 91 cm at the Caswell Farm, 41 cm at Wilson County and Port Royal sites, and 20 cm at the Lenoir and Wayne county sites.

Each field was mapped using Pocket WeedMap software and GPS. Each field was divided into grid cells (Table 1), and densities of each weed species within each grid cell were visually estimated 2 to 3 wk after planting. At Caswell and CEFS in 1999 and 2001, weeds were also identified and counted in 10 randomly selected 9.3-m^2 quadrats in each field.

Grid cell length was increased from 30.5 to 61 m in 2000 because trials with an experimental variable-rate herbicide applicator indicated that the longer plots would reduce problems caused by a delay between the time when the applicator crossed into a grid cell and the time the herbicide rate was adjusted according to a treatment map. When the sprayer crossed the border of the treatment cell, data for the rate required by that cell were processed. Time delays were present in the chemical injection system and in the carrier system between the chemical injection point and the nozzles. As the updated rate of chemical was introduced into the carrier, time delays to blend the product and change to the updated rate were also present. These time delays and the time required to blend the chemical to the updated rate had to be accounted for by adjusting the look ahead time in the control software. As a result, relatively gradual rate changes were produced rather than sharp step changes. The longer cells also provided a more stable system response by allowing additional time for changes in rate to stabilize.

Data Analysis. HADSS Version 2003 (Bennett et al. 2003; Sturgill et al. 2003) was used to determine the theoretical net return over herbicide investment (TNR) for every potential postemergence treatment in each grid cell of all fields. It was also used to determine TNR for the 10 randomly selected quadrats in four fields. To calculate TNR, HADSS uses an approach that has been described previously (Bennett et al. 2003; Jordan et al. 2003). The treatment with the highest TNR across all grid cells was considered to be the optimal whole-field treatment because the calculation of net return using this method takes into account all available information on actual weed densities and spatial distribution. We calculated TNR for site-specific weed management in two ways: first, assuming that each grid cell receives the herbicide treatment with the highest TNR for that specific cell (TNR_{SSNR}) and second, assuming that each grid cell receives the herbicide treatment with the lowest remaining yield loss after treatment for that specific cell (TNR_{SSYL}). YL was also estimated by HADSS for each grid cell and for each whole-field treatment. YL is a function of treatment efficacy and the density and relative competitive ability of each remaining weed species (Bennett et al. 2003) and can serve as an indicator of potential differences in seed production (Canner et al. 2002). In addition, we calculated the percentage of grid cells for which the whole-field treatment was optimal and compared herbicide costs for the optimal whole-field treatment with that for the two site-specific weed management strategies.

In all comparisons, herbicide recommendations were determined for each of the six herbicide-efficacy conditions available in HADSS: wet or dry soil moisture and three weed size categories (<5, 5 to 10, and >10 cm tall). Projected weed-free soybean seed yield was set at 2,690 kg/ha with a market price of $0.22/kg. In addition, herbicide recommendations were determined either with or without glyphosate being considered as a herbicide option, to compare results for conventional and GR soybean varieties.

RESULTS AND DISCUSSION

Weed Populations and Estimated Yield Losses Without Treatment. Weed densities were determined in 575 grid cells across the 14 fields. The prevalence of weed species within these cells is shown in Table 2. High densities of carpetweed (*Mollugo verticillata* L.), pitted morningglory (*Ipomoea lacunosa* L.), ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], redroot pigweed (*Amaranthus retroflexus* L.), sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby], and broadleaf signalgrass [*Brachiaria platyphylla* (L.) Griseb.] were found at the Caswell Farm in 1999. Although densities varied somewhat across the field, most species were present in most grid cells, resulting in an estimated average yield loss without treatment of 70% (Table 3). The field at CEFS in 1999 had high densities of spreading dayflower (*Commelina communis* L.), eclipta (*Eclipta prostrata* L.), ivyleaf morningglory, and broadleaf signalgrass, but only ivyleaf morningglory and broadleaf signalgrass were found in almost all cells. Dayflower was concentrated in one corner of the field (Figure 1).

At the Caswell Farm in 2000, weed populations were again very high across the field, with the major weed species being carpetweed, eclipta, entireleaf and pitted morningglory, sicklepod, and broadleaf signalgrass. Pitted morningglory and sicklepod were present in all grid cells. At CEFS in 2000, weeds included carpetweed, spreading dayflower, eclipta, seedling johnsongrass [*Sorghum halepense* (L.) Pers.], entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray), pitted morningglory, redroot pigweed, sicklepod, prickly sida (*Sida spinosa* L.), and broadleaf signalgrass. Entireleaf morningglory and broadleaf signalgrass were present in more than 90% of the cells but spreading dayflower was present in less than 40% of the cells. At Port Royal in 2000, similar weed species were found in the full-season and double-crop plots. Weeds scouted included carpetweed, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], entireleaf morningglory, honeyvine milkweed [*Ampelamus albidus* (Nutt.) Britt.], horsenettle (*Solanum carolinense* L.), redroot pigweed, and yellow nutsedge (*Cyperus esculentus* L.). Pitted morningglory was found in a few of the full-season cells, and tropic croton (*Croton glandulosus* var. *septentrionalis* Muell.-Arg.) was found in a few double-crop cells. Carpetweed and large crabgrass densities were much higher in the full-season plots, likely because of a burndown treatment applied before planting in the double-cropped soybean, which reduced populations within those plots. Estimated yield losses ranged from 0 to 28% without treatment in the double-crop grid cells and from 1 to 38% in the full-season grid cells.

At the Caswell Farm in 2001, prevalent weeds included sicklepod, entireleaf and pitted morningglory, large crabgrass, and broadleaf signalgrass. Palmer amaranth (*Amaranthus palmeri* S.Wats.), goosegrass [*Eleusine indica* (L.) Gaertn.], eastern black nightshade (*Solanum ptycanthum* Dun.), yellow nutsedge, and redroot pigweed were found in less than 15% of the grid cells. Estimated yield loss across the field ranged from 3 to 62% if no control measures were taken, with a field average loss of 31%. At CEFS in 2001, redroot pigweed, carpetweed, and prickly sida were found in almost all

Table 2. Grid cells infested by each weed species in 14 soybean fields scouted in the coastal plain of North Carolina and Virginia from 1999 through 2002.

Weed species	Latin binomial	Bayer code[a]	Number of fields	Grid cells infested	Infested cell density: Mean	Infested cell density: Maximum
				%	no./9.3 m²	
Redroot pigweed	*Amaranthus retroflexus* L.	AMARE	12	38	25	632
Carpetweed	*Mollugo verticillata* L.	MOLVE	10	45	138	1,406
Pitted morningglory	*Ipomoea lacunosa* L.	IPOLA	10	22	10	284
Sicklepod	*Senna obtusifolia* (L.) Irwin and Barneby	CASOB	9	38	21	421
Prickly sida	*Sida spinosa* L.	SIDSP	9	18	3	26
Broadleaf signalgrass	*Brachiaria platyphylla* (L.) Griseb.	BRAPP	8	27	158	3,600
Entireleaf morningglory	*Ipomoea hederacea* var. *integriuscula* Gray	IPOHG	8	26	2	16
Large crabgrass	*Digitaria sanguinalis* (L.) Scop.	DIGSA	7	36	94	2,812
Yellow nutsedge	*Cyperus esculentus* L.	CYPES	7	16	3	50
Ivyleaf morningglory	*Ipomoea hederacea* (L.) Jacq.	IPOHE	6	23	5	56
Honeyvine milkweed	*Ampelamus albidus* (Nutt.) Britt.	AMPAL	5	29	5	111
Eclipta	*Eclipta prostrata* L.	ECLAL	5	15	128	1,969
Horsenettle	*Solanum carolinense* L.	SOLCA	5	3	<1	2
Spreading dayflower	*Commelina communis* L.	COMDI	4	12	23	232
Johnsongrass	*Sorghum halepense* (L.) Pers.	SORHA	4	10	5	100
Common lambsquarters	*Chenopodium album* L.	CHEAL	4	9	2	22
Common chickweed	*Stellaria media* (L.) Vill.	STEME	2	3	5	32
Goosegrass	*Eleusine indica* (L.) Gaertn.	ELEIN	2	3	19	95
Trumpetcreeper	*Campsis radicans* (L.) Seem. ex Bureau	CMIRA	2	2	10	75
Palmer amaranth	*Amaranthus palmeri* S.Wats.	AMAPA	2	1	2	3
Common pokeweed	*Phytolacca americana* L.	PHTAM	2	<1	<1	<1
Red morningglory	*Ipomoea coccinea* L.	IPOCC	1	7	24	93
Tall morningglory	*Ipomoea purpurea* (L.) Roth	PHBPU	1	5	14	56
Horseweed	*Conyza canadensis* (L.) Cronq.	ERICA	1	4	1	7
Spurred anoda	*Anoda cristata* (L.) Schlecht.	ANVCR	1	4	345	2,812
Tropic croton	*Croton glandulosus* var. *septentrionalis* Muell.-Arg.	CVNGS	1	1	1	3
Dogfennel	*Eupatorium capillifolium* (Lam.) Small	EUPCP	1	1	<1	<1
Cutleaf groundcherry	*Physalis angulata* L.	PHYAN	1	1	4	8
Eastern black nightshade	*Solanum ptycanthum* Dun.	SOLPT	1	1	<1	1
Common purslane	*Portulaca oleracea* L.	POROL	1	1	21	93
Common cocklebur	*Xanthium strumarium* L.	XANST	1	1	<1	<1
Smooth pigweed	*Amaranthus hybridus* L.	AMACH	1	<1	1	2
Arrowleaf sida	*Sida rhombifolia* L.	SIDRH	1	<1	58	113
Common ragweed	*Ambrosia artemisiifolia* L.	AMBEL	1	<1	<1	<1
Spotted spurge	*Euphorbia maculata* L.	EPHMA	1	<1	<1	<1
Velvetleaf	*Abutilon theophrasti* Medicus	ABUTH	1	<1	<1	<1

[a] The Bayer Code is a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

Table 3. Weed populations in North Carolina and Virginia coastal plain soybean fields scouted from 1999 through 2002.[a]

Site, year	Number of species	Estimated yield loss without treatment per cell			Cells infested by each weed species		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
			%			%	
Caswell, 1999	7	70	58	76	75	6	100
Caswell, 2000	9	63	25	78	71	8	100
Caswell, 2001	11	31	3	62	34	6	100
CEFS, 1999	9	34	5	72	47	3	97
CEFS, 2000	10	50	3	75	66	39	95
CEFS, 2001	14	46	20	66	45	3	100
Port Royal, full-season, 2000	8	10	1	38	47	3	100
Port Royal, double-crop, 2000	8	4	<1	28	24	2	57
Port Royal, full-season, 2001	9	23	<1	60	45	3	90
Port Royal, double-crop, 2001	8	10	<1	62	30	1	70
Port Royal, full-season, 2002	15	7	<1	47	29	3	93
Lenoir County, 2002	13	67	17	79	43	3	93
Wayne County, 2002	7	56	21	76	62	10	98
Wilson County, 2002	10	7	<1	57	39	5	90

[a] Abbreviation: CEFS, Center for Environmental Farming Systems.

cells. Spreading dayflower, broadleaf signalgrass, sicklepod, and entireleaf morningglory were found in more than 50% of the cells. Estimated yield loss varied from 20 to 66% among grid cells and averaged 46% for the field as a whole. At the Virginia location in 2001, scouted weeds were similar to those found in 2000, except that common lambsquarters (*Chenopodium album* L.) (Figure 2) and prickly sida were found in the full-season plots. Estimated yield loss without treatment varied from less than 1% to over 60% in both full-season and double-crop plots.

At the Lenoir County site in 2002, spurred anoda [*Anoda cristata* (L.) Schlecht.], carpetweed, large crabgrass, eclipta, and sicklepod were found in more than 70% of the cells. Dayflower was present in 47% of the cells, and Palmer amaranth, dogfennel [*Eupatorium capillifolium* (Lam.) Small], johnsongrass, pitted and ivyleaf morningglory, common purslane (*Portulaca oleracea* L.), and arrowleaf sida (*Sida rhombifolia* L.) were present in less than 30% of cells. Red morningglory (*Ipomoea coccinea* L.), redroot pigweed, and sicklepod were found in almost all grid cells at the Wayne County field in 2002. Goosegrass, tall morningglory [*Ipomoea purpurea* (L.) Roth], prickly sida, and broadleaf signalgrass were also present. At the Wilson County site in 2002, weed densities were generally low, probably because of the use of a preemergence herbicide, with an estimated average yield loss without additional treatment of 7%. Common lambsquarters and morningglory species were present at low densities in more than 80% of the grid cells. Other species found included common cocklebur (*Xanthium strumarium* L.), horsenettle, sicklepod, trumpetcreeper

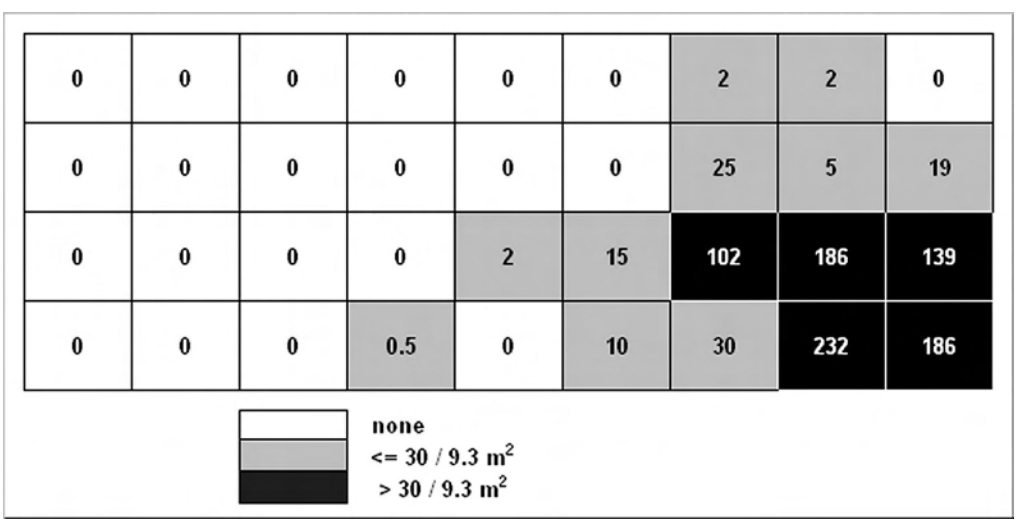

Figure 1. Density of spreading dayflower in grid cells in the field at the Center for Environmental Farming Systems, as determined by scouting on June 28, 1999.

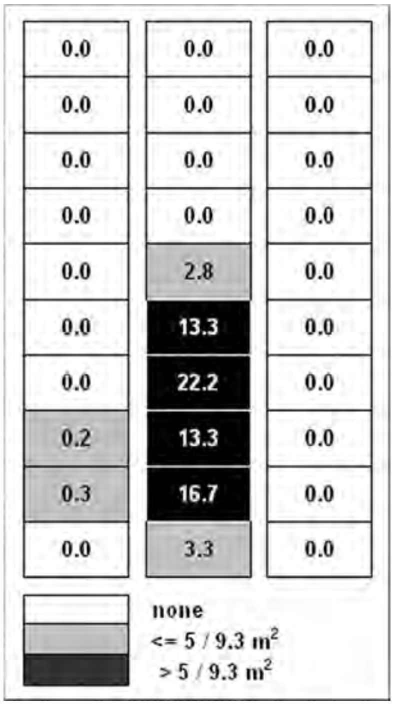

Figure 2. Density of common lambsquarters in grid cells of the full-season soybean plots in the field at Port Royal, VA, as determined by scouting on June 14, 2001.

[*Campsis radicans* (L.) Seem. ex Bureau], and yellow nutsedge.

Site-Specific Management Based on Optimizing Net Returns. For conventional soybean, TNR for the optimal whole-field treatment, averaged across six soil moisture–weed size conditions, varied from a low of $0/ha (no herbicide application recommended) for the Port Royal double-crop soybean plots in 2000 to a high of $187/ha for the Wayne County field in 2002 (Table 4). It varied from $0/ha to $290/ha for GR soybean. TNR for the optimal whole-field treatment averaged across all fields and conditions was $79/ha and $139/ha for conventional and GR soybean, respectively. Site-specific herbicide applications increased TNR by an average of $13/ha and $4/ha for conventional and GR soybean, respectively, when the treatment with the highest expected net return was applied to each grid cell. The lower gains from site-specific management found for GR soybean compared with conventional soybean are similar to the results of Jordan et al. (2003), who found lower gains in TNR for site-specific management of 52 peanut fields when paraquat was allowed than when it was not allowed. Similar to glyphosate, paraquat is a broad-spectrum, inexpensive herbicide. Although average returns were low enough that they would be unlikely to cover the increased scouting and application costs for site-specific management, returns for some fields under some conditions were high enough to perhaps more than cover these costs, particularly for conventional soybean (Figure 3).

Although net return estimates based on a current-year economic threshold strategy were generally low for these fields, site-specific management using this strategy might help decrease weed problems in future years in many of these fields, based on projected decreases in YL (Table 5). Estimated YL was reduced by as much as 38.6% for conventional soybean and 23.2% for GR soybean. On average, YL was reduced by 10.5 and 3.9% for conven-

Table 4. Theoretical net returns (TNR_{SSNR}) estimated by HADSS for site-specific weed management when the treatment with highest expected net return is applied to each grid cell for the 14 North Carolina and Virginia fields scouted during 1999 through 2002.[a]

Site, year	TNR for optimal whole-field treatment			Gain in TNR for site-specific treatment		
	Mean	Conventional	Glyphosate resistant	Mean	Conventional	Glyphosate resistant
	$/ha					
Caswell, 1999	231	174	288	3	4	2
Caswell, 2000	237	184	290	8	15	<1
Caswell, 2001	114	78	150	11	22	1
CEFS, 1999	108	91	125	18	23	13
CEFS, 2000	190	149	231	11	18	4
CEFS, 2001	192	164	220	6	8	4
Port Royal, full-season, 2000	25	16	35	7	11	3
Port Royal, double-crop, 2000	0	0	0	1	1	1
Port Royal, full-season, 2001	57	31	83	15	26	5
Port Royal, double-crop, 2001	3	1	6	7	7	8
Port Royal, full-season, 2002	11	6	17	11	13	8
Lenoir County, 2002	128	22	234	9	15	2
Wayne County, 2002	225	187	263	6	11	1
Wilson County, 2002	4	4	4	7	5	9
Mean	109	79	139	9	13	4

[a] Abbreviations: CEFS, Center for Environmental Farming Systems; HADSS, Herbicide Application Decision Support System; TNR, theoretical net return over herbicide investment.

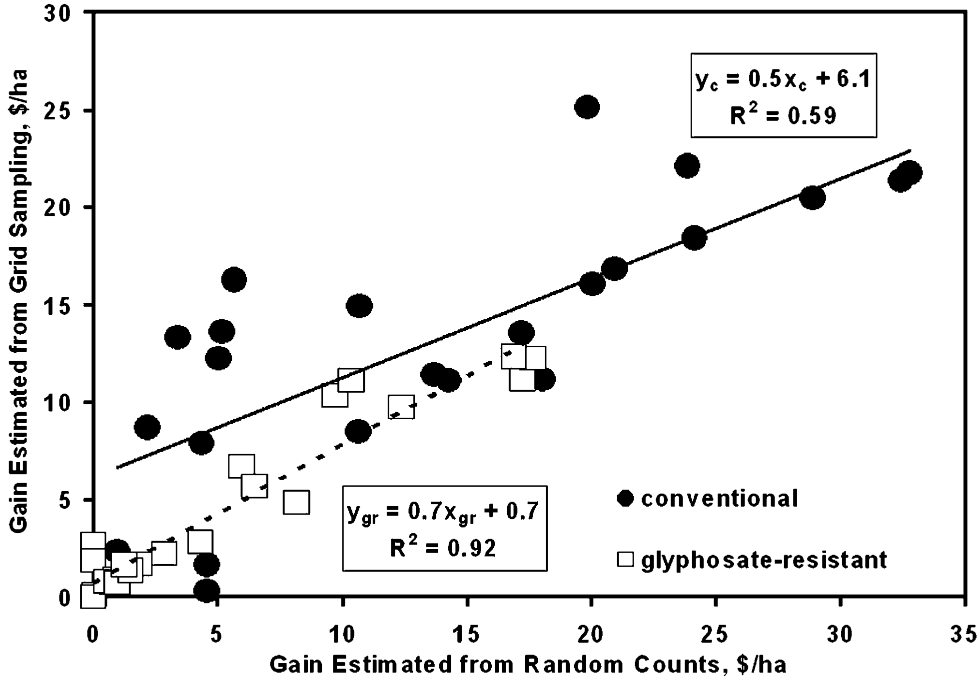

Figure 3. Distribution of gain in theoretical net returns (TNR_{SSNR}) over whole-field treatment for site-specific weed management when the treatment with the highest expected net return is applied to each grid cell under varying assumptions of weed size and soil moisture for 14 North Carolina and Virginia fields scouting during 1999 through 2002.

tional and GR soybean, respectively. In several cases, projected YL actually increased with site-specific management. This was especially true when the whole-field recommendation was to apply a herbicide and the site-specific strategy resulted in no herbicide application in many cells (e.g., Port Royal full-season soybean, all years, for GR soybean).

Table 5. Estimated changes in yield loss (compared with optimal whole-field treatment) for site-specific weed management when the treatment with highest expected net return is applied to each grid cell for the 14 North Carolina and Virginia fields scouted during 1999 through 2002.[a]

	Change in yield loss for site-specific treatment		
Site, year	Mean	Conventional	Glyphosate resistant
	%		
Caswell, 1999	−2.9	1.3	−7.1
Caswell, 2000	−4.7	−8.0	−1.3
Caswell, 2001	−5.9	−10.0	−1.9
CEFS, 1999	−16.5	−9.9	−23.2
CEFS, 2000	−9.9	−7.8	−11.9
CEFS, 2001	−10.1	−6.0	−14.2
Port Royal, full-season, 2000	4.8	−2.6	12.2
Port Royal, double-crop, 2000	−12.5	−6.6	−18.5
Port Royal, full-season, 2001	−10.3	−27.0	6.5
Port Royal, double-crop, 2001	−8.4	−12.2	−4.6
Port Royal, full-season, 2002	−2.5	−38.6	33.6
Lenoir County, 2002	−0.2	−3.9	3.4
Wayne County, 2002	−11.6	−13.4	−9.7
Wilson County, 2002	−10.1	−2.6	−17.6
Mean	−7.2	−10.5	−3.9

[a] Abbreviation: CEFS, Center for Environmental Farming Systems.

The level of diversity in recommendations for grid cells varied greatly between fields. For conventional soybean, the optimal whole-field treatment was recommended for only 35% of the grid cells, on average, but this varied from a low of 7% for Caswell 2001 to a high of 84% for Port Royal double-crop soybean in 2000 (Table 6). For GR soybean, the optimal whole-field treatment was recommended for an average of 57% of the grid cells but ranged from a low of 16% for Port Royal full-season soybean in 2002 to a high of 99% for Caswell 2000.

Fields where site-specific management offered the highest gain in net return for GR soybean were CEFS 1999, in which a high population of dayflower was present in 14% of grid cells (Figure 1), and Wilson County 2002, in which the recommendation was not to treat in 70% of cells but the whole-field recommendation was to apply a herbicide (not glyphosate for most soil moisture–weed size conditions). For the three conventional soybean fields with an average gain in net return for site-specific management over $20/ha, the percent of cells for which the whole-field recommendation was optimal was substantially lower than in the other fields: 7, 10, and 12% (Table 6).

Table 6. Percent of grid cells estimated by HADSS for which the optimal whole-field treatment is also the optimal treatment for that specific cell, when the treatment with highest expected net return is applied to each grid cell for the 14 North Carolina and Virginia fields scouted during 1999 through 2002.[a]

Site, year	Grid cells for which the whole-field treatment is optimal: Mean	Conventional	Glyphosate resistant
	%		
Caswell, 1999	76	58	94
Caswell, 2000	72	44	99
Caswell, 2001	38	7	69
CEFS, 1999	21	10	32
CEFS, 2000	50	23	77
CEFS, 2001	60	61	60
Port Royal, full-season, 2000	35	19	50
Port Royal, double-crop, 2000	80	84	76
Port Royal, full-season, 2001	29	12	47
Port Royal, double-crop, 2001	35	46	25
Port Royal, full-season, 2002	19	21	16
Lenoir County, 2002	53	48	58
Wayne County, 2002	62	39	84
Wilson County, 2002	21	22	19
Mean	46	35	57

[a] Abbreviations: CEFS, Center for Environmental Farming Systems; HADASS, Herbicide Application Decision Support System.

In some cases, site-specific management could have reduced the amount of herbicide applied by reducing the number of cells to which herbicide was applied (e.g., 70% reduction for Wilson County 2002 for GR soybean) or by reducing the rate of application in some cells. In other cases, more herbicide was recommended for site-specific management when a herbicide not included in the whole-field recommendation was recommended for some cells. For example, the whole-field recommendation for Port Royal double-crop soybean in 2000 was not to apply herbicide for all conditions for both conventional and double-crop soybean, but a herbicide treatment was recommended for 20 to 25% of the grid cells. Overall herbicide costs averaged $3/ha and $1/ha less for site-specific management for conventional and GR soybean, respectively, and were $13/ha less for the 1999 CEFS conventional soybean.

Site-Specific Management Based on Minimizing Yield Loss. If, to reduce weed seed production, a grower prefers to use a weed control strategy based on maximizing weed control, rather than on maximizing net returns in the current crop, then site-specific management might make sense, particularly if the most effective treatment is applied in each grid cell. Because most herbicide treatments are not 100% effective against all weed species present in a particular field, even when two or more chemicals are combined, a strategy based on efficacy needs to consider the competitive ability of each species as well as level of control. HADSS allows treatments to be sorted by YL, which is a function of initial density of each species, treatment efficacy, and relative competitive ability of each species (Bennett et al. 2003; Wilkerson et al. 1991). Table 7 shows the costs and benefits of taking this approach to weed management for these 14 fields. When the treatment with the lowest YL was applied in each grid cell, average herbicide costs increased $30/ha and $7/ha over those for the optimal whole-field treatment for conventional and GR soybean, respectively (data not shown). Part, but not all, of this increase in herbicide costs was offset by increases in yield. TNR was reduced by $18/ha and $4/ha on average for conventional and GR soybean, respectively, using this strategy. Reduction in TNR was as high as $65/ha

Table 7. Changes in theoretical net returns (TNR_{SSYL}) and yield loss (compared with optimal whole-field treatment) for site-specific weed management when the treatment with the lowest yield loss is applied to each grid cell for the 14 North Carolina and Virginia fields scouted during 1999 through 2002.[a]

Site, year	Change in TNR for site-specific treatment: Mean	Conventional	Glyphosate resistant	Change in yield loss for site-specific treatment: Mean	Conventional	Glyphosate resistant
	$/ha			%		
Caswell, 1999	−3	−6	1	−5.0	−1.9	−8.1
Caswell, 2000	2	3	<1	−10.7	−18.4	−2.9
Caswell, 2001	0	1	−1	−28.9	−30.1	−27.7
CEFS, 1999	−3	−1	−6	−28.0	−24.7	−31.3
CEFS, 2000	0	1	−2	−23.9	−24.3	−23.5
CEFS, 2001	1	1	1	−24.6	−16.6	−32.7
Port Royal, full-season, 2000	−26	−42	−9	−42.4	−58.1	−26.7
Port Royal, double-crop, 2000	−41	−65	−18	−31.4	−23.0	−39.9
Port Royal, full-season, 2001	−8	−10	−5	−20.7	−38.7	−2.6
Port Royal, double-crop, 2001	−24	−41	−8	−18.8	−23.6	−14.0
Port Royal, full-season, 2002	−28	−48	−8	−41.6	−64.8	−18.3
Lenoir County, 2002	−6	−11	0	−5.3	−7.4	−3.2
Wayne County, 2002	−3	−6	−1	−15.9	−24.2	−7.6
Wilson County, 2002	−15	−26	−5	−23.6	−16.4	−30.8

[a] Abbreviations: CEFS, Center for Environmental Farming Systems; TNR, theoretical net return over herbicide investment.

and $18/ha for Port Royal double-crop soybean in 2000 for conventional and GR soybean, respectively. Costs would be higher if extra scouting and application costs for site-specific management were included. HADSS estimated that this strategy would reduce yield loss by 27% on average for conventional soybean and by 19% for GR soybean.

Random Sampling to Determine Suitability of Field for Site-Specific Management. For the four fields in which 10 random 9.3-m^2 samples were taken, it appears that this quicker, less-costly scouting technique, suitable for making whole-field decisions (Krueger et al. 2000), may help identify those fields for which site-specific management may be most appropriate. For GR soybean, there was a strong correlation between expected gain in TNR calculated using grid cell weed densities and gain in TNR calculated using the 10 random samples (Figure 3). For conventional soybean, the correlation was less strong, but for all cases in which gain in TNR estimated using the random samples was greater than $20/ha, the gain in TNR using the grid cell weed densities was greater than $15/ha. Time required for the two methods of scouting used in this study was 0.25 h/ha for the random sampling and 1.0 h/ha for the grid cell sampling.

This study indicates that site-specific herbicide applications may improve soybean weed management by decreasing yield loss after treatment, reducing weed seed production, and increasing net returns. However, in the majority of fields, the theoretical gain in return from site-specific management was marginal. The time and labor required for developing weed population maps continues to be a primary constraint to adoption of site-specific weed management technology. Results indicate that random sampling in as few as 10 spots per field may provide sufficient information to identify fields that might benefit from more intensive scouting and variable-rate herbicide applications.

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