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Detection of pitted morningglory (*Ipomoea lacunosa*) with hyperspectral remote sensing. II. Effects of vegetation ground cover and reflectance properties

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Field research was conducted to determine the potential of hyperspectral remote sensing for discriminating plots of soybean intermixed with pitted morningglory and weed-free soybean with similar and different proportions of vegetation ground cover. Hyperspectral data were collected using a handheld spectroradiometer when pitted morningglory was in the cotyledon to two-leaf, two- to four-leaf, and four- to six-leaf growth stages. Synthesized reflectance measurements containing equal and unequal proportions of reflectance from vegetation were obtained, and seven 50-nm spectral bands (one ultraviolet, two visible, and four near-infrared) derived from each hyperspectral reflectance measurement were used as discrimination variables to differentiate weed-free soybean and soybean intermixed with pitted morningglory. Discrimination accuracy was 93 to 100% regardless of pitted morningglory growth stage and whether equal or unequal proportions of reflectance from vegetation existed in weed-free soybean and soybean intermixed with pitted morningglory. Discrimination accuracy was 88 to 98% when using the discriminant model developed for one experiment to discriminate soybean intermixed with pitted morningglory and weed-free soybean plots of the other experiment. Reflectance in the near-infrared spectrum was higher for weed-free soybean compared with soybean intermixed with pitted morningglory, and this difference affected the ability to discriminate weed-free soybean from soybean intermixed with pitted morningglory.

Nomenclature: Pitted morningglory, *Ipomoea lacunosa* L. IPOLA; soybean, *Glycine max* (L.) Merr. 'Asgrow 4702RR'.

Key words: Conventional tillage, discriminant analysis, linear mixing, no tillage, remote sensing.

Remote sensing technologies have been used to detect weeds in rangelands (Everitt et al. 1996; Lass et al. 1996), wetlands (Balough and Bookhout 1989), and row-crop production systems (Medlin et al. 2000; Richardson et al. 1985). Remotely sensed detection of rangeland weeds is often conducted late in the growing season when there is a substantial difference in the phenological stage of development between the weed species of interest and neighboring vegetation. Little information is available regarding what factors affect detection of weeds in row-crop systems. Detection of row-crop weeds early in the growing season, when weeds are small and when most weed control decisions are made, is often challenged by soil background reflectance that saturates crop–weed reflectance measurements. In addition, the amount of vegetation ground cover often varies between areas of fields containing weed-free crop and crop intermixed with weeds. Koger et al. (2004) used hyperspectral remote sensing to discriminate plots of weed-free soybean and soybean intermixed with pitted morningglory at 71 to 95% accuracy across a variety of soil background reflectance environments (combinations of tillage and cover crop residues). It was not possible to determine what factor(s) affected weed discrimination capabilities because reflectance measurements were collected from field plots of weed-free soybean and soybean intermixed with pitted morningglory containing unequal proportions of reflectance from vegetation (Koger et al. 2004).

Linear mixing of pure reflectance measurements of crop, weed(s), and soil to derive synthetically mixed reflectance measurements may be a methodology that can determine what factor(s) affects row-crop weed detection. Linear mixing is a straightforward mathematical approach, where a linear combination (or weighted sum) of the pure components (soybean, pitted morningglory, and soil) is formed. The components can be mixed at any percentage or combination to derive mixed reflectance measurements (Schowengerdt 1997). Linear-mixing models have been used to test subpixel target (pure component) detection algorithms in a variety of settings (Bruce et al. 2001; Li 2002; Manolakis et al. 2001; Settle and Campbell 1998). Bruce et al. (2001) used the linear-mixing model to investigate the use of multiresolutional analysis for detecting aerosol targets mixed with a variety of background components. Linear-mixing models also have been used to investigate the effectiveness of feature extraction to improve the results of unmixing algorithms, which were used to decompose a mixed reflectance measurement and estimate the abundances or proportions of the underlying pure components (Li 2002). The primary advantage of the linear-mixing model is that the exact mixing proportions of each pure component is known, so quantitative analysis can be conducted. Linear-mixing models, which contain various proportions of reflectance from vegetation (crops and weeds) and soil, can be developed and may be useful for determining what affects row-crop weed detection.

Table 1. Growth stage, height, and ground cover estimates for soybean and pitted morningglory in soybean intermixed with pitted morningglory and weed-free soybean plots at each hyperspectral data acquisition timing at Starkville and Stoneville.[a]

Soybean intermixed with pitted morningglory						Weed-free soybean		
Soybean			Pitted morningglory			Soybean		
Growth stage[b]	Height	Ground cover	Growth stage	Height	Ground cover	Growth stage[b]	Height	Ground cover
no. of leaves	cm	%	no. of leaves	cm	%	no. of leaves	cm	%
Starkville								
2–3	5–15	28	Coty.–3	5–8	25	2–3	7–14	32
3–4	9–16	30	2–4	5–10	30	3–4	12–16	34
4–6	22–29	36	4–6	8–12	38	4–6	23–27	39
Stoneville								
2–4	7–18	35	Coty.–2	2–8	22	2–4	8–16	37
3–6	9–20	40	2–4	2–15	35	3–6	10–22	45
5–8	15–25	51	4–6	5–20	35	5–9	13–28	58

[a] Abbreviation: Coty., cotyledon.
[b] Number of trifoliolate leaves.

The objectives of this research were to use pure reflectance measurements of soybean, pitted morningglory, and soil for developing linear-mixed synthetic reflectance measurements containing equal and unequal proportions of reflectance from vegetation (soybean and pitted morningglory) so that the dependent and independent effects of vegetation ground cover and reflectance properties of soybean and pitted morningglory on weed detection capabilities could be investigated.

Materials and Methods

A field experiment was conducted in 2001 at the USDA-ARS Southern Weed Science Research Unit farm near Stoneville, MS, and the Plant Science Research Center, Starkville, MS. Experimental procedures are described in Koger et al. (2004). For this study, hyperspectral data were collected from the conventional-till weed-free soybean and soybean intermixed with pitted morningglory plots at both experimental locations.

Hyperspectral Data Acquisition

Beginning when soybean plants had two to three trifoliolate leaves and pitted morningglory was in the cotyledon to two-leaf growth stage, four hyperspectral reflectance measurements of soybean, four of pitted morningglory, and four of soil were collected from each soybean intermixed with pitted morningglory plot within each experiment. Four measurements of soybean and four of soil were collected from each weed-free soybean plot. Reflectance measurements were collected using an ASD Field Spec Pro FR portable spectroradiometer.[1] The sensor was held 8 cm above each object of interest (soil, soybean, or pitted morningglory), resulting in a 1.12-cm spatial resolution for each measurement. Each measurement collected hyperspectral reflectance data between 350 and 2,500 nm, resulting in 2,151 individual spectral bands for each measurement. Bands between 350 and 1,050 nm had a bandwidth of 1.4 nm, and bands between 1,051 and 2,500 nm had a bandwidth of 1.0 nm. Reflectance measurements also were collected from each plot of both experiments at the two- to four-leaf and four- to six-leaf pitted morningglory growth stages. Reflectance from the uppermost leaflet of the youngest, fully expanded, trifoliate soybean leaf and the youngest, fully expanded pitted morningglory leaf in each plot was measured at each timing (pitted morningglory growth stage). Plant height and visual ground cover estimates of pitted morningglory and soybean in each plot also were recorded at each timing (Table 1).

Synthetic linear-mixed reflectance measurements containing different proportions of vegetation (soybean and pitted morningglory) and soil reflectance were developed from the pure soybean, pitted morningglory, and soil reflectance measurements with Matlab[2] software. Synthetic reflectance measurements were developed for each pitted morningglory growth stage and experimental location according to the ground cover proportions of soybean, pitted morningglory, and soil visually estimated in the field. For example, averages of the soybean and pitted morningglory ground cover estimates in the soybean intermixed with pitted morningglory plots at Starkville were 28 and 25% at the cotyledon to two-leaf pitted morningglory growth stage, respectively; whereas, estimate of soybean ground cover in the weed-free soybean plots was 32% (Table 1). Thus, four synthetic reflectance measurements comprising 28, 25, and 47% reflectance for soybean, pitted morningglory, and soil (soybean intermixed with pitted morningglory) and four measurements comprising 32 and 68% reflectance for soybean and soil (weed-free soybean) were developed for the cotyledon to two-leaf growth stage at Starkville. Four synthetic reflectance measurements for soybean intermixed with pitted morningglory and four for weed-free soybean were developed for each pitted morningglory growth stage and experimental location. These synthetic reflectance measurements will be referred to as "uneven proportions of vegetation reflectance" because the degree of reflectance from vegetation differed between soybean intermixed with pitted morningglory and weed-free soybean.

A second synthetic mixed pixel reflectance measurement data set was developed that contained "equal proportions of reflectance from vegetation." Linear-mixed reflectance measurements were synthesized containing equal proportions of reflectance from vegetation for soybean intermixed with pitted morningglory and weed-free soybean plots. For example, soybean and soil accounted for 32% and soil 68% ground

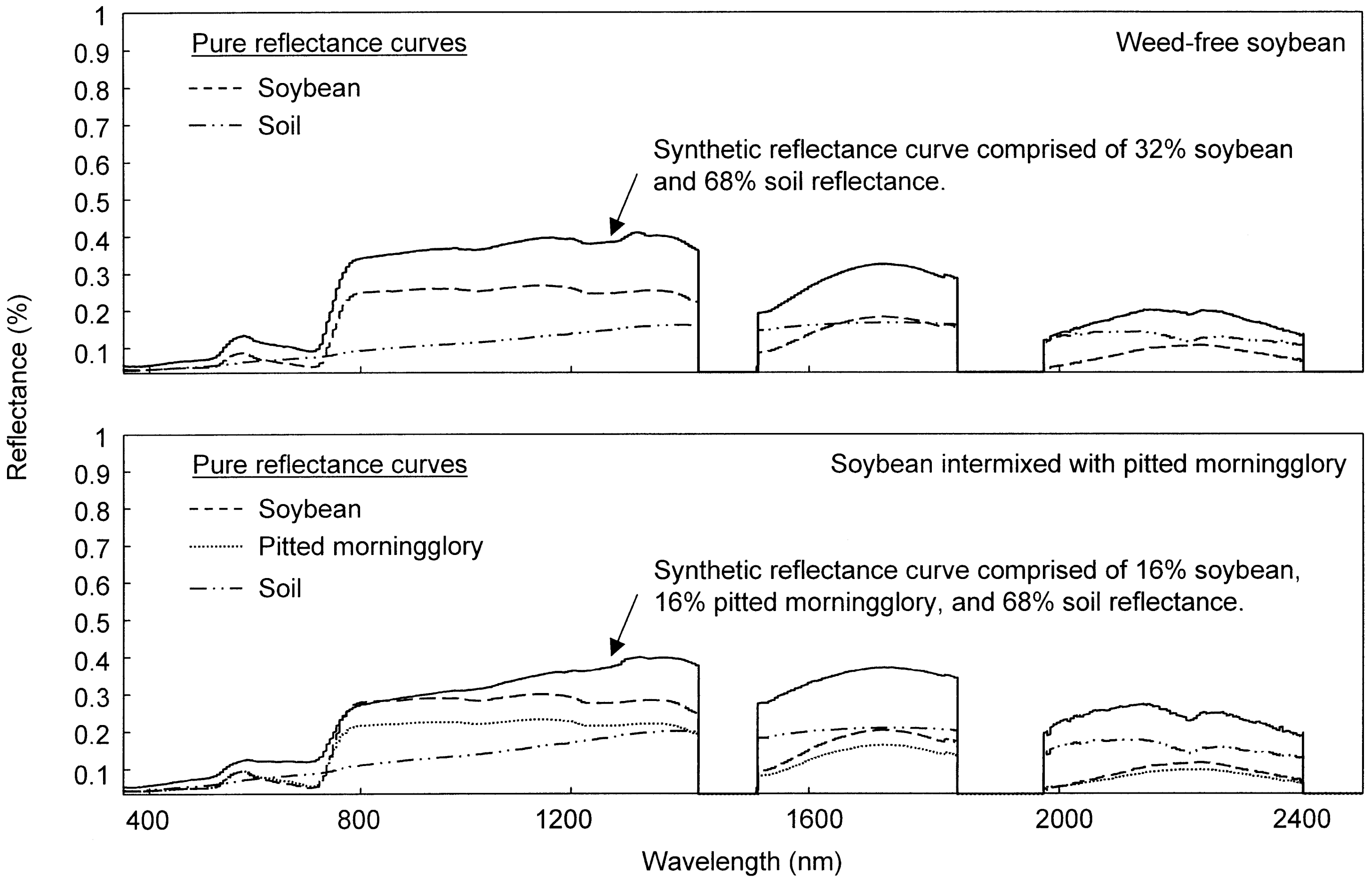

FIGURE 1. Pure reflectance measurements of soybean, pitted morningglory, and soil used in constructing synthetic reflectance measurements for weed-free soybean and soybean intermixed with pitted morningglory containing equal proportions of vegetation reflectance at the cotyledon to two-leaf pitted morningglory growth stage at Starkville, MS.

cover, respectively, in weed-free soybean plots at Starkville for the cotyledon to two-leaf pitted morningglory growth stage (Table 1). Thus, four reflectance measurements containing 32% soybean and 68% soil reflectance (weed-free soybean) and four containing 16% soybean, 16% pitted morningglory, and 68% soil reflectance (soybean intermixed with pitted morningglory) were synthesized for the cotyledon to two-leaf pitted morningglory growth stage at Starkville. Four synthetic reflectance measurements for weed-free soybean and four for soybean intermixed with pitted morningglory were developed for each pitted morningglory growth stage and experimental location. Examples of synthetic reflectance measurements for soybean intermixed with pitted morningglory and weed-free soybean containing equal proportions of vegetation reflectance can be found in Figure 1.

Reflectance proportions (soybean, pitted morningglory, and soil) for soybean intermixed with pitted morningglory and weed-free soybean synthetic reflectance measurements containing unequal and equal amounts of vegetation reflectance are listed in Table 2. Pure hyperspectral signals for soybean, pitted morningglory, and soil were used only once for constructing synthetic reflectance measurements (unequal and equal proportions of vegetation reflectance) so that no bias would be introduced into the data.

Data Analysis

Seven 50-nm-wide spectral bands, centered at 375, 425, 575, 725, 925, 975, 1,125, and 1,375 nm, were extracted from each synthetic hyperspectral reflectance measurement. These 50-nm bands were used to discriminate soybean intermixed with pitted morningglory and weed-free soybean in previous research (Koger et al. 2004). The 1.0- and 1.4-nm bands were averaged to result in one reflectance value for each 50-nm band. The seven resulting bands from each synthetic reflectance measurement were used as discrimination variables in Fisher's linear discriminant analysis (Franz et al. 1991) for discriminating reflectance measurements of weed-free soybean from soybean intermixed with pitted morningglory when unequal and equal proportions of vegetation reflectance were present. Linear discriminant analyses were performed on data from each pitted morningglory growth stage and experimental location. To test the versatility of the 50-nm bands, linear discriminant models developed for one experiment location were applied to the data collected from the other experiment. All analysis procedures were conducted in SAS,[3] and cross-validation summaries of discrimination results were used in all linear discriminant analysis scenarios. Mean separations of 50-nm bands extracted from weed-free soybean and soybean intermixed with pitted morningglory synthetic reflectance measurements were performed using Fisher's Protected LSD test at the 0.05% level of significance.

Results and Discussion

Weed-free soybean and soybean intermixed with pitted morningglory were discriminated correctly 93 to 100%

Table 2. Proportions of soybean, pitted mg, and soil reflectance for weed-free soybean and soybean intermixed with pitted mg synthetic reflectance measurements containing unequal and equal proportions of vegetation reflectance at Starkville and Stoneville.[a]

Reflectance measurement component	Reflectance measurements containing unequal proportions of vegetation and soil reflectance						Reflectance measurements containing equal proportions of vegetation and soil reflectance					
	Coty. to 2-LF[b]		2- to 4-LF		4- to 6-LF		Coty. to 2-LF		2- to 4-LF		4- to 6-LF	
	WFS[c]	SPM[c]	WFS	SPM	WFS	SPM	WFS	SPM	WFS	SPM	WFS	SPM
	% of total reflectance											
Starkville												
Soybean	32	28	34	30	38	36	32	16	34	17	38	19
Pitted mg	0	25	0	30	0	38	0	16	0	17	0	19
Soil	68	47	66	40	62	26	68	68	66	66	62	62
Stoneville												
Soybean	38	35	44	40	58	51	38	19	44	22	58	29
Pitted mg	0	22	0	35	0	35	0	19	0	22	0	29
Soil	62	43	56	20	42	14	62	62	56	56	42	42

[a] Abbreviations: Coty., cotyledon; LF, leaf; mg, morningglory; SPM, soybean intermixed with pitted mg; WFS, weed-free soybean.
[b] Pitted morningglory growth stage.
[c] Plot type.

across all pitted morningglory growth stages and both experiments when unequal amounts of reflectance from vegetation existed between weed-free soybean and soybean intermixed with pitted morningglory (Table 3). Synthetic reflectance measurements for weed-free soybean and soybean intermixed with pitted morningglory containing unequal proportions of reflectance from vegetation emulated actual field conditions. More reflectance from vegetation existed in soybean intermixed with pitted morningglory plots when compared with weed-free soybean plots. Synthetic reflectance measurements representing true field conditions, where more reflectance from vegetation existed for one plot type than for another, were discriminated with a high level of accuracy. These results are similar to those reported in a previous work by Koger et al. (2004), where weed-free soybean and soybean intermixed with pitted morningglory field plots containing unequal amounts of vegetation were discriminated correctly 71 to 95% across various tillage and cover crop residue systems and pitted morningglory growth stages. However, previous research (Koger et al. 2004) and results presented in this study, where proportions of reflectance from vegetation differed between weed-free and weed-infested crop, do not provide sufficient information to determine whether discrimination capabilities are due to differences in the amount of vegetation for weed-free and weed-infested crop or reflectance properties of the crop compared with those of the weeds.

Discrimination capabilities also were very high with equal proportions of reflectance from vegetation present for weed-free soybean (all vegetation reflectance from soybean) and soybean intermixed with pitted morningglory (half vegetation reflectance from soybean and half from pitted morningglory). Weed-free soybean and soybean intermixed with pitted morningglory containing equal amounts of reflectance from vegetation were discriminated correctly 93 to 99% (Table 3). Based on these results, amplitude differences in percent reflectance from the crop compared with that from the weed species may be affect-

Table 3. Discrimination of synthetic reflectance measurements of weed-free soybean and soybean intermixed with pitted morningglory containing unequal and equal proportions of vegetation reflectance at each pitted morningglory growth stage and experiment.[a]

Pitted morningglory growth stage	Correct discrimination[b]			
	Unequal proportion of vegetation reflectance[c]		Equal proportion of vegetation reflectance[c]	
	Weed-free soybean	Soybean intermixed with pitted morningglory	Weed-free soybean	Soybean intermixed with pitted morningglory
no. of leaves	%			
Starkville				
Coty.–2	97	96	96	93
2–4	97	99	99	97
4–6	100	100	94	98
Stoneville				
Coty.–2	96	98	98	96
2–4	95	100	93	94
4–6	98	93	94	99

[a] Abbreviation: Coty., cotyledon.
[b] Seven 50-nm-wide bands centered on 375, 425, 575, 725, 925, 975, and 1,125 nm were used as discrimination variables in all linear discriminant analyses.
[c] Actual proportions of reflectance from vegetation (soybean and pitted morningglory) for each pitted morningglory growth stage and experiment are listed in Table 2.

TABLE 4. Discrimination of synthetic reflectance measurements of WFS and SIPM using linear discriminant model developed for one experiment to discriminate WFS from SIPM of the other experiment at each pitted morningglory growth stage.[a]

Pitted morningglory growth stage	Correct discrimination[b]			
	Unequal proportion of vegetation reflectance[c]		Equal proportion of vegetation reflectance[c]	
	WFS	SIPM	WFS	SIPM
no. of leaves	%			
Starkville[d]				
Coty.–2	88	90	92	96
2–4	94	97	97	96
4–6	95	98	93	91
Stoneville[e]				
Coty.–2	91	91	98	91
2–4	94	94	98	96
4–6	90	98	94	95

[a] Abbreviations: Coty., cotyledon; WFS, weed-free soybean; SIPM, soybean intermixed with pitted morningglory.
[b] Seven 50-nm-wide bands centered on 375, 425, 575, 725, 925, 975, and 1,125 nm were used as discrimination variables in all linear discriminant analyses.
[c] Actual proportions of reflectance from vegetation (soybean and pitted morningglory) for each pitted morningglory growth stage and experiment are listed in Table 2.
[d] Discrimination of Starkville data using discriminant model developed for Stoneville.
[e] Discrimination of Stoneville data using discrimination model developed for Starkville.

ing the ability to discriminate weed-free crop from crop intermixed with weeds.

Weed-free soybean and soybean intermixed with pitted morningglory were discriminated correctly 88 to 98% when using discriminant model developed from one experiment to discriminate synthetic reflectance measurement data from the other experiment, regardless of pitted morningglory growth stage and whether unequal or equal proportions of reflectance from vegetation for weed-free crop and crop plus weeds were present (Table 4). These results reveal the versatility of the seven 50-nm bands for discriminating weed-free crop from crop containing weeds across different locations, weed growth stages, and even when equal proportions of reflectance from vegetation existed in plots of weed-free crop and crop plus weeds. The ability to discriminate the two types of plots containing equal proportions of reflectance from vegetation with a discriminant model developed for the other experiment provides support that discrimination capabilities are due more to differences in reflectance properties of the crop and weed species than to differences in the amount of vegetation present in weed-free vs. weed-infested plots.

Within the seven 50-nm bands, there were differences in reflectance for synthetic reflectance measurements of weed-free soybean and soybean intermixed with pitted morningglory. Reflectance in all bands except the 725-nm band was often higher across all pitted morningglory growth stages for weed-free soybean compared with soybean intermixed with pitted morningglory when proportions of reflectance from vegetation were unequal between weed-free soybean and soybean intermixed with pitted morningglory (Table 5). When reflectance measurements contained equal proportions of reflectance from vegetation, reflectance between the 700- to 1,400-nm spectral range was higher for weed-free soybean than soybean intermixed with pitted morningglory regardless of pitted morningglory growth stage (Table 6). However, when equal proportions of reflectance from vegetation existed, there were no differences in reflectance between weed-free soybean and soybean intermixed with pitted morningglory in the 375-, 425-, and 525-nm bands. Therefore, based on reflectance for the seven 50-nm bands when proportions of reflectance from vegetation for weed-free crop and crop plus weeds were equal, soybean had a higher degree of reflectance in the infrared portion of the

TABLE 5. Reflectance for seven 50-nm-wide spectral bands of weed-free soybean and soybean intermixed with pitted mg synthetic reflectance measurements containing unequal proportions of vegetation reflectance, averaged across pitted mg growth stage and experiment.[a,b]

Pitted mg growth stage	Synthetic reflectance measurement	Reflectance						
		375 nm	425 nm	575 nm	725 nm	925 nm	975 nm	1,125 nm
no. of leaves		%						
Coty.–2	Soybean + soil	0.08 a	0.12 a	0.15 a	0.22 a	0.33 a	0.39 a	0.42 a
	Soybean + pitted mg + soil	0.03 b	0.07 b	0.1 b	0.21 a	0.15 b	0.22 b	0.27 b
2–4	Soybean + soil	0.11 a	0.13 a	0.18 a	0.24 a	0.37 a	0.41 a	0.47 a
	Soybean + pitted mg + soil	0.04 b	0.09 b	0.12 b	0.22 a	0.17 b	0.25 b	0.33 b
4–6	Soybean + soil	0.13 a	0.17 a	0.22 a	0.28 a	0.43 a	0.49 a	0.54 a
	Soybean + pitted mg + soil	0.08 a	0.10 b	0.13 b	0.23 a	0.27 b	0.29 b	0.35 b

[a] Abbreviations: Coty., cotyledon; mg, morningglory.
[b] Means followed by the same letter within a column for each pitted mg growth stage are not significantly different, according to Fisher's Protected LSD test at $\alpha = 0.05$.

TABLE 6. Reflectance for seven 50-nm-wide spectral bands of weed-free soybean and soybean intermixed with pitted mg synthetic reflectance measurements containing equal proportions of vegetation reflectance, averaged across pitted mg growth stage and experiment.[a,b]

Pitted mg growth stage	Synthetic reflectance measurement	Reflectance						
		375 nm	425 nm	575 nm	725 nm	925 nm	975 nm	1,125 nm
no. of leaves		%						
Coty.–2	Soybean + soil	0.02 a	0.05 a	0.11 a	0.25 a	0.33 a	0.39 a	0.41 a
	Soybean + pitted mg + soil	0.02 a	0.04 a	0.13 a	0.14 b	0.18 b	0.25 b	0.31 b
2–4	Soybean + soil	0.03 a	0.07 a	0.16 a	0.34 a	0.42 a	0.43 a	0.44 a
	Soybean + pitted mg + soil	0.04 a	0.05 a	0.12 a	0.25 b	0.35 b	0.36 b	0.38 b
4–6	Soybean + soil	0.06 a	0.09 a	0.19 a	0.37 a	0.42 a	0.49 a	0.53 a
	Soybean + pitted mg + soil	0.06 a	0.07 a	0.15 a	0.22 b	0.28 b	0.33 b	0.37 b

[a] Abbreviations: Coty., cotyledon; mg, morningglory.
[b] Means followed by the same letter within a column for each pitted mg growth stage are not significantly different, according to Fisher's Protected LSD test at $\alpha = 0.05$.

spectrum (725, 925, 975, and 1,125 nm). These differences in reflectance between crop and crop plus weeds had more effect on the ability to discriminate weed-free crop from crop plus weeds than differences in degree of vegetation ground cover.

The linear-mixing technique proved to be a useful tool for developing reflectance measurements containing proportions of vegetation and soil reflectance similar to levels actually observed in the field. More importantly, linear mixing addressed questions regarding what factors affect weed discriminant capabilities and the understanding of how weeds can be differentiated from crop to facilitate real time weed detection systems. These results also provide information regarding questions raised by previous research conducted by Koger et al. (2004), where field plots of weed-free soybean and soybean intermixed with pitted morningglory were discriminated with at least 71% accuracy across various pitted morningglory growth stages and soil background reflectance environments (tillage and cover crop residue systems). However, the authors were unable to determine which factor(s), such as varying amounts of vegetation ground cover or differences in reflectance properties of the crop and weeds, actually influenced discriminant capabilities because the amount of vegetation ground cover differed according to treatment. In this study, the use of the linear-mixing technique revealed that amplitude differences in reflectance between soybean and pitted morningglory affected discriminant capabilities more than the degree of vegetation ground cover in weed-free and weed-infested plots.

Sources of Materials

[1] Field Spec Pro., Analytical Spectral Devices Inc., 5335 Sterling Drive, Boulder, CO 80301-2344.

[2] Matlab, The Mathworks, Inc., 3 Apple Drive, Natick, MA 01760-2098.

[3] SAS, SAS Institute, Inc., SAS Campus Drive, Cary, NC 27513.

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