Agricultural Sciences, 2019, 10, 1465-1476
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Canopy Hyperspectral Reflectance of Redroot Pigweed versus Okra and Super Okra Leaf Cotton

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How to cite this paper: Fletcher, R.S. (2019) Canopy Hyperspectral Reflectance of Redroot Pigweed versus Okra and Super Okra Leaf Cotton. *Agricultural Sciences*, **10**, 1465-1476.
https://doi.org/10.4236/as.2019.1011107

Received: September 25, 2019
Accepted: November 18, 2019
Published: November 21, 2019

Abstract

Redroot pigweed (*Amaranthus retroflexus* L.) is a nuisance weed that affects cotton (*Gossypium hirsutum* L.) growth and yield worldwide. Being able to distinguish redroot pigweed from cotton would help producers and crop consultants better implement strategies used to suppress and control it. Hyperspectral reflectance properties of weed and crop canopies have been used to differentiate between them. Currently, no information is available on the application of hyperspectral data to distinguish redroot pigweed from cotton with different leaf shapes. Positive results will further support the exploration of remote sensing technology for distinguishing redroot pigweed from cotton. The objectives were to compare canopy hyperspectral reflectance of redroot pigweed to canopy hyperspectral reflectance of okra and super okra leaf cotton and to identify regions of the spectrum in which differences exist in their reflectance properties. Hyperspectral reflectance measurements of redroot pigweed and cotton were obtained with a spectroradimeter on May 6 and June 27, 2019. Plants grown in a greenhouse were used for this study. One-hundred and sixty-two 10-nm bands (400 - 2350 nm spectral range) were evaluated with analysis of variance ($p \le 0.05$) and Dunnett's test ($p \le 0.05$) to determine the wavebands that were useful for separating redroot pigweed from okra leaf and super okra leaf cotton. The following bands were consistent in distinguishing redroot pigweed and okra leaf cotton on both dates: 420 nm, 510 - 650 nm, 690 - 740 nm, and 2000 - 2010 nm; whereas, 400 - 500 nm, 1480 - 1780 nm, and 1990 - 2350 nm were identified for both dates for separating redroot pigweed from super okra leaf cotton. Commercial imaging systems used on ground-based or airborne platforms can be easily tuned into the spectral bands listed in this study, thus providing managers with a tool to use for identifying redroot pigweed in cotton production systems.

Keywords

Amaranthus retroflexus, *Gossypium hirsutum*, Visible, Red Edge, Shortwave Infrared

1. Introduction

Cotton is grown worldwide for its fiber production and is used more than any other fiber producing plant [1]. Cotton production contributes enormously to the agricultural sector because of the supplies purchased to grow it. Furthermore, cotton is used to make clothing, bedding, plastics, paper products, furniture, automobile cushions, cottonseed oil, animal feed, fertilizers, and explosives. After the growing season, its stalks are plowed under to enrich the soil. Weed infestation is a common problem in a cotton production system because it reduces cotton growth and yield.

Redroot pigweed, one of the most invasive weeds in agricultural production worldwide [2], is known to reduce yields in bean species (*Phaseolus* spp.) [3] [4] [5], soybean (*Glycine max* L.) [6], corn (*Zea mays* L.) [7] [8] [9], and cotton [10] [11] [12]. It is a nuisance because one plant produces thousands of seeds, ensuring the next generation of plants [13]. If seeds are present in the soil and environmental conditions ideal for seed germination, then redroot pigweed seeds will sprout throughout the growing season [14], requiring multiple treatments to control it. If new plants are allowed to mature, then they will add more seeds to the seed bank. Redroot pigweed seeds are viable for a long time thus requiring treatment for many years after an infestation [15] [16].

Redroot pigweed grows quickly allowing it to outcompete agricultural plants for water and nutrients. Its allelopathic characteristics also give it an advantage in crop production systems [17] [18] [19]. Redroot pigweed has developed resistance to acetolactate synthase (ALS) inhibitors, photosystem II inhibitors (PSII), and protoporphyrinogen oxidase (PPO) [20] in some areas of the world, making it a challenge to control. Redroot pigweed can grow up to 3 m tall. Therefore, it is a tall weed. Tall weeds tend to be more damaging to cotton growth and development [21] because they cover the shorter cotton plant canopies. The light reaching the shorter cotton plants is reduced causing them not to be able to compete for water and nutrients at the same level as the weed.

Redroot pigweed can reduce cotton yield by 5% - 90% percent [10] [11] [12]; plant density of the redroot pigweed and soil pattern are associated with its effects on cotton yield [10] [11] [12]. Producers and crop consultants are seeking tools to help them identify redroot pigweed in cotton production systems. Being able to distinguish redroot pigweed from cotton would help producers and crop consultants better implement strategies used to suppress and control it.

Spectral reflectance properties of weed and crop canopies have been used to differentiate between them. Advances in multispectral and hyperspectral technologies have increased the use of remote sensing technologies in weed crop discrimination. Little canary grass (*Phalaris minor* Retz.) [22], button weed (*Malva neglecta*) [23], and spiny emex (*Rumex spinosus* L.) [24] [25] were distinguished from wheat (*Triticum aestivum* L.), based on their red and near infrared canopy reflectance. Those studies focused on using the red and near infrared bands as a ratio and a normalized difference vegetation index. Furthermore, the findings of those studies indicated that pure populations of little canary grass, button weed, and spiny emex were distinguishable from pure wheat stands 34, 30, and 30 days after planting, respectively. Also, different population levels of button weed and spiny emex were discernable from themselves 60 days after planting based on their reflectance properties; density levels of little canary grass were separable from themselves 68 days after planting using the reflectance data. The differences in the weed populations reflectance were detectable up to 120 days after planting.

Researchers have used spectral reflectance data of crop canopies as input in various classification algorithms for crop and weed separation. Reference [26] distinguished wild oat (*Avena sterilis* L.) and canary grass in wheat fields using multispectral, hyperspectral, and vegetation index data and discriminate analysis. Reference [27] demonstrated that multispectral data could be used as input into random forest classifier to distinguish velvetleaf (*Abutilon theophrasti* Medic.) from soybean [*Glycine max* L. (Merr.)]; reference [28] showed that hyperspectral data and random forest was useful for separating Palmer amaranth (*Amaranthus palmeri* S. Wats.) from cotton with different colored leaves. Reference [29] discriminated Barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv], green foxtail [*Setaria viridis* (L.) P. Beauv], goosegrass [*Eleusine indica* (L.) *Gaertn*], crabgrass (*Digitaria sanguinalis* L.), and quinoa (*Chenopodium quinoa* Willd.) from cabbage (*Brassica oleracea* L.) using hyperspectral reflectance data as input into Bayesian discriminant analysis.

As indicated earlier, spectral reflectance properties of plant canopies have been used to distinguish crops from weeds. Understanding these properties is often the basic premise for implementing remote sensing technology for weed detection and mapping in agricultural systems. Also, by conducting these studies, researchers can determine if more information is needed to enhance the spectral information for crop weed discrimination. Reference [30] have published research on the difference in reflectance properties of Palmer amaranth, another pigweed, versus okra and super okra leaf cotton. Currently, no information is available on the application of hyperspectral data to distinguish redroot pigweed from cotton with different leaf shapes. The objectives were to compare canopy hyperspectral reflectance of redroot pigweed to canopy hyperspectral reflectance of okra and super okra leaf cotton and to identify regions of the spectrum in which differences exist in their reflectance properties. The study specifically focused on comparing visible, red edge, near infrared, and shortwave infrared reflectance properties of the plant canopies.

2. Materials and Methods

2.1. Study Site, Planting Dates, Experimental Design

The experiment was conducted in a greenhouse located at the United States Department of Agriculture, Agricultural Research Service Facility, Stoneville, MS (33.425261 latitude, −90.912740 longitude). Redroot pigweed, okra leaf cotton, and super okra leaf cotton seeds were bulk planted into seed trays (Garland, Standard Half Size Seed Trays, Greenhouse Megastore, Danville, IL, 1 seed tray for each plant type) filled with commercial potting mix (Pro-Mix BX general professional growth medium, Premier Tech Horticulture, Quakertown, PA). Planting dates were February 27 and May 13, 2019, for experiments one and two, respectively. Ten days after emergence healthy plants were transplanted to 2-liter pots (Belden Jumbo Senior Square Pots, Greenhouse Mega, Danville, IL) containing the same commercial potting mix. Plants were subjected to 14-hour day length; sodium vapor lamps (average luminous flux = 84,100) were used as supplemental lighting in the mornings (6:00AM - 8:00AM) and the evenings (6:00PM - 8:00PM). The greenhouse temperature was maintained within the following range: 21.1˚C and 26.7˚C. Redroot pigweed, okra leaf cotton, and super okra leaf cotton seeds were obtained from seed banks maintained by scientists working at the Stoneville laboratory. The redroot pigweed was not resistant to any herbicides. The plants were watered and fertilized (Dyna-Gro All-Pro 7-7-7, Richmond, CA) weekly. The experimental design was a randomized complete block design consisting of fifteen blocks and three treatments per block (*i.e.*, plants—redroot pigweed, okra leaf cotton, and super okra leaf cotton).

2.2. Reflectance Measurements

Reflectance measurements of the plant canopies were acquired on May 6, 2019, and June 27, 2019, ±2 hours of solar noon [31] for experiments one and two, respectively. They were obtained with a FieldSpec 3 Full Range Hyperspectral Spectroradiometer (Analytical Spectral Devices, Malvern Panalytical, Boulder, CO). The spectroradiometer collected spectral data in the 350 - 2500 nm spectral range. Its sensor was placed nadir 30.48 cm above the plant canopy to obtain the reflectance measurements. At that height, the sensor's ground field of view was 13.5 cm. For each plant, the reflectance measurement was an average of fifteen scans obtained by the spectroradiometer. Calibration of the instrument was completed at 15-minute intervals with a white spectralon reflectance panel (Analytical Spectral Devices, Malvern Panalytical, Boulder, Colorado). The plants were taken outside of the greenhouse to obtain the measurements; instrument calibration and reflectance measurements were acquired under sunny conditions. As described in [30], black felt was used to cover the potting mix background and to serve as the background surface for placing the pots. Its reflectance value was approximately 3% in all regions of spectrum evaluated in this study.

The goal of the study was to obtain reflectance measurements of the redroot pigweed and the cotton during the vegetative growth stage. Once pigweed plants start to seed, it is difficult to control them with herbicides. The redroot pigweed was at the fifteenth and sixteenth leaf stage for experiments one and two, respectively. Okra and super okra leaf cotton plants were at the ninth and eight leaf stage for first the experiment. For the second experiment, the plants were developing squares. Weather conditions hindered data being collected earlier, preferably between the fourth and fifth leaf stage for the cotton.

2.3. Preparing Hyperspectral Data for Analysis

The data were processed using the following steps [30] [32]: 1) splice correction of the spectra, 2) removal of water absorption bands (*i.e.*, 1330 - 1480 nm, 1780 - 1990 nm), 3) elimination of noisy data and spectral bands commonly not used for remote sensing (*i.e.*, 350 - 400 nm, 2360 - 2500 nm), 4) smoothing the spectra with the Savitizky-Golay [33] filter (n = 25, number points used for data smoothing), and 5) aggregating the 1-nm spectral bands recorded by spectroradiometer to 10-nm spectral bands. Splice correction was completed with the ViewSpec Pro Software (Version 6.2, Analytical Spectral Devices, Malvern Panalytical Boulder, CO). Steps two thru four above were completed with the R software (Version 3.6.1, "Action of the Toes" [34]) HSDAR package [35].

2.4. Statistical Analyses

For each waveband, analysis of variance (ANOVA, $p \leq 0.05$) was used to determine if reflectance differences were statistically significant among the plant group means [36] [37]. If yes, then the Dunnett's test [38] was used to determine if a statistically significant ($p \leq 0.05$) difference existed between redroot pigweed and okra leaf cotton, and redroot pigweed and super okra leaf cotton. For experiment one, a redroot pigweed plant died. Therefore, 14 blocks were analyzed for that experiment. The agricolae package [39] of the R software was used to complete the ANOVA and Dunnett's analyses.

3. Results

Mean hyperspectral reflectance curves of redroot pigweed and okra and super okra leaf cotton canopies are shown in **Figure 1** for the two experiments. Overall, okra leaf cotton canopies mean reflectance values were greater than the redroot pigweed canopies mean reflectance values in the visible, red edge, and near infrared regions of the light spectrum. Super okra leaf cotton canopies mean reflectance values were less than redroot pigweed canopies mean reflectance values in the near infrared and the shortwave infrared regions of the light spectrum for both sets of measurements.

Based on the ANOVA, statistically significant differences ($p \leq 0.05$) were observed among the plant groups for all 162 bands evaluated (**Table 1**). Further exploration of the bands with the Dunnett's test identified 95 and 31 spectral bands with statistically significant ($p \leq 0.05$) differences between redroot pigweed and okra leaf cotton reflectance for the May and the June measurements, respectively (**Table 2**). For the redroot pigweed and super-okra leaf cotton comparison, the Dunnett's test identified 85 and 99 spectral bands in which the differences in reflectance values were statistically significant ($p \leq 0.05$) for the May and June measurements, respectively (**Table 2**).

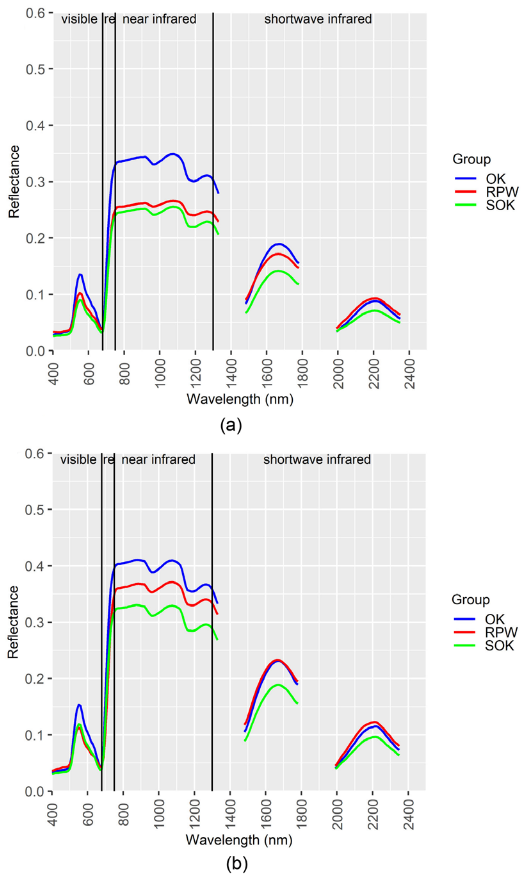

Figure 1. Mean canopy hyperspectral reflectance spectrum of okra leaf cotton (OK), redroot pigweed (RPW), and super okra leaf cotton (SOK) obtained on (a) May 6, 2019 (n = 14) and (b) June 27, 2019 (n = 15). red = red edge.

Table 1. Analysis of variance ($p \leq 0.05$) results listing the spectral regions, spectral bands, and number of bands in which statistical differences were observed among redroot pigweed, okra leaf cotton, and super okra leaf cotton canopy reflectance.

Date	Spectral Region	Spectral Bands (nm)	Number of Bands
May 6, 2109; June 27, 2019	Visible	400 - 670	28
	Red edge	680 - 750	8
	Near infrared	760 - 1300	55
	Shortwave infrared	1310 - 1330; 1480 - 1780; 1990 - 2350	71
		Total	162

Table 2. Dunnett's test ($p \leq 0.05$) results listing the spectral regions, spectral bands, and the number of bands in which statistical differences occurred between redroot pigweed (RPW) versus okra leaf cotton (OK) comparison and redroot pigweed versus super okra leaf cotton (SOK) comparison.

Date	Comparison	Spectral Region	Spectral Bands (nm)	Number of Bands
May 6, 2019	RPW vs OK	Visible	400 - 420; 510 - 650	18
		Red edge	690 - 750	7
		Near infrared	760 - 1300	55
		Shortwave infrared	1310 - 1330; 1990 - 2090; 2350	15
			Total	95
	RPW vs SOK	Visible	400 - 520; 650 - 670	16
		Red edge	680	1
		Near infrared		0
		Shortwave infrared	1480 - 1780; 1990 - 2350	68
			Total	85
June 27, 2019	RPW vs OK	Visible	420 - 490, 510 - 650	23
		Red edge	690 - 740	6
		Near infrared		0
		Shortwave infrared	2000 - 2010	2
			Total	31
	RPW vs SOK	Visible	400 - 500	11
		Red edge	670 - 680, 700 - 710	4
		Near infrared	1160 - 1300	15
		Shortwave infrared	1310 - 1330, 1480 - 1780, 1990 - 2350	69
			Total	99

For the May 6 and June 27, 2019 dates, the following bands were consistent in distinguishing redroot pigweed and okra leaf cotton: 420 nm, 510 - 650 nm, 690 - 740 nm, and 2000 - 2010 nm (Table 2). Bands in which the reflectance value differences were statistically significant ($p \leq 0.05$) for the redroot pigweed and super okra leaf cotton comparison on both dates were 400 - 500 nm, 1480 - 1780 nm, and 1990 - 2350 nm (Table 2). The 420 nm and 2000 - 2010 nm spectral bands were considered universal because reflectance differences were statistically significant for redroot pigweed and both cotton comparisons on both dates (Table 2).

4. Discussion

Spectral bands within the visible, red edge, and shortwave infrared regions of the light spectrum were identified for distinguishing redroot pigweed from okra leaf and super okra leaf cotton (**Table 2**). Various plant components influence visible, red edge, and shortwave infrared reflectance properties of plant leaves [40] [41]. Plant pigments are the major contributor to leaf reflectance spectral responses in the visible region of the light spectrum [40] [41]. A combination of plant pigments and intercellular spaces within the plant leaves and multiple leaf layers affects the red edge response of plant leaves and canopies [42]. Water content within the plant leaves causes the differences observed in the shortwave infrared reflectance properties of plant leaves and canopies [40] [41]. Thus, leaf pigment, intercellular spaces in plant leaves, multiple leaf layers in the plant canopies, and leaf water content caused the spectral differences observed between redroot pigweed and the cotton canopies.

Near infrared reflectance data were inconsistent in separating redroot pigweed and the cotton plants. Similar results were observed by [30] for near infrared spectra in comparison of Palmer amaranth, another common pigweed, and okra leaf and super okra leaf cotton.

Also, in-canopy shadowing and background affected differences observed between redroot pigweed and okra and super okra leaf cotton. Their contribution is based on the architecture of the plant canopies (**Figure 2**). Redroot pigweed and okra leaf cotton canopies consisted of broad leaves that have a horizontal leaf orientation; whereas, super okra leaf cotton canopies have narrow leaves and a horizontal leaf orientation. Furthermore, spaces between the plant leaves contributed to the reflectance differences observed between the redroot pigweed and okra and super okra leaf cotton canopies. More open spaces equal more shadows and background being recorded by the sensor, causing a decrease in the reflectance of the plant canopies.

Twenty spectral bands were identified by [43] as optimal for vegetation mapping: 490 nm, 515 nm, 531 nm, 550 nm, 570 nm, 682 nm, 720 nm, 855 nm, 910 nm, 970 nm, 1075 nm, 1180 nm, 1245 nm, 1450 nm, 1650 nm, 1725 nm, 1950 nm, 2205 nm, 2260 nm, and 2359 nm. For redroot pigweed versus okra leaf cotton comparison, 510 - 650 nm and 690 - 740 nm spectral bands were similar to the optimal spectral bands; for the redroot pigweed versus the super okra leaf comparison, 420 nm, 1450 nm, 1650 nm, 1720 - 1730 nm, 2200 - 2210 nm, and

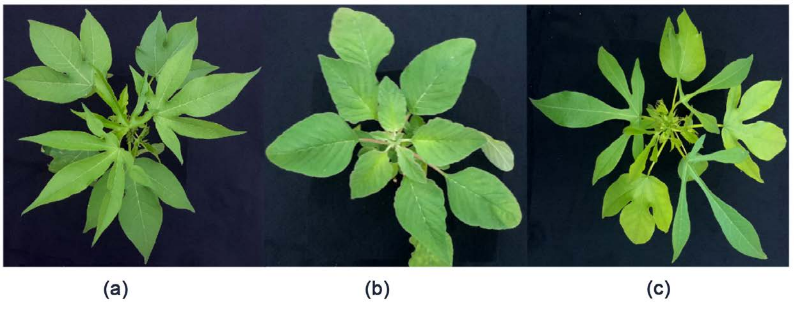

Figure 2. Overhead example of (a) okra leaf cotton; (b) redroot pigweed; and (c) super okra leaf cotton canopies.

2260 nm spectral bands were comparable to the optimal spectral bands. The optimal spectral bands discussed by [43] were based on 5 nm bandwidths in comparison to the 10 nm bandwidths used for the current study.

Multispectral camera systems can be tuned into the spectral bands identified for differentiating redroot pigweed from okra and super okra leaf cotton. Sensors sensitive to visible, red edge, and near infrared light are inexpensive to purchase and build compared to systems sensitive to visible, red edge, near infrared, and shortwave infrared light. The difference in cost is attributed to the shortwave infrared sensor. Shortwave infrared sensors are constructed from indium gallium arsenide, which is more expensive than silicon material used to construct visible, red edge, and near infrared-sensitive sensors. For example, a single camera sensitive to shortwave infrared reflectance cost more than $20,000.

Overall, a hyperspectral camera system may be more beneficial in that commercial systems often acquire data in wavebands similar to the ones evaluated in this study. Also, it would not be limited to the weed and crop tested in this study. However, the same rule applies to cost. Visible, red edge, and near infrared sensitive hyperspectral systems are much cheaper than visible, red edge, near infrared, and shortwave infrared sensitive hyperspectral systems.

5. Conclusion

This study focused on using canopy hyperspectral reflectance measurements as a means for distinguishing redroot pigweed from okra and super okra leaf cotton. The results indicated that it could be distinguished from okra leaf and super okra leaf cotton based on its canopy hyperspectral reflectance properties. Spectral bands within the visible, red edge, and shortwave infrared regions of the light spectrum were determined to be optimal for redroot pigweed and okra and super okra leaf cotton separation. There are commercial imaging systems designed for ground-based or airborne platforms that can be easily tuned into the spectral bands listed in this study, thus providing managers with a tool to use in precision agriculture applications of redroot pigweed in cotton production systems.

Acknowledgements

The author would like to thank Dr. Ricky Turley, Dr. Vijay Nandula, Milton Gaston Jr., Destraile Jackson, Mekaela Brisco, and Eric Benson for their assistance in this study. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture and does not apply endorsement of a product to the exclusion of others that may be suitable.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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