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Utilizing remote sensing technology for monitoring chemically managed giant salvinia (*Salvinia molesta*) populations

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ABSTRACT

Thousands of acres of giant salvinia (*Salvinia molesta*) are managed annually in Louisiana and Texas, but management success is difficult to measure quantitatively. The objective of this research was to evaluate and develop remote sensing techniques to quickly and accurately assess giant salvinia health and herbicide efficacy in a field scenario. Field sampling data from Saline Lake, LA documented a negative correlation ($R^2 = -0.785$) between Landsat near-infrared (NIR) reflectance and visual percent control ratings. Additional research utilizing high-resolution WorldView-3 reflectance data indicated that percent control and NIR reflectance of giant salvinia in sampled plots were significantly correlated at 2 and 6 wk after treatment, with $P = 0.047$ and $P < 0.0001$, respectively. Additional data collected with a DJI Phantom drone and low-cost RGNIR Sentera Single Sensor during an 8-wk mesocosm study documented the strongest linear relationship ($R^2 = -0.914$) between percent control and NIR reflectance values, and the resulting linear regression equation was used to predict percent control values utilizing data collected in previous studies. The relationship between predicted and observed percent control values was linear and significant ($P \leq 0.0001$) and yielded R and R^2 values of 0.918 and 0.843, respectively. On the basis of the NIR spectral response of giant salvinia to herbicide applications, remote sensing can provide beneficial information on the success or failure of large-scale herbicide applications.

Key words: drone, efficacy, herbicide, near-infrared, predict, reflectance, regression, satellite imagery.

INTRODUCTION

Giant salvinia (*Salvinia molesta* D.S. Mitchell) is a floating aquatic fern that has spread from its native range in South America to over 20 countries worldwide (Oliver 1993), including the United States (Johnson 1995). The ornamental plant trade is the likely vector for the intercontinental spread of giant salvinia. Botanical gardens and commercial horticulture have been linked to its introduction in Asia, Africa, North America, and Australia (Harley and Mitchell 1981, Nelson 1984, Thomas and Room 1986, Oliver 1993). It thrives in the southern United States, exhibits rapid growth, and forms dense mats that negatively affect water resources immediately after infestation. Extensive giant salvinia growth impedes waterborne navigation, transportation, irrigation, and recreational activities within infested water bodies (Pimentel et al. 1999). From an ecological and economic standpoint, this free-floating fern has the ability to degrade water quality and wildlife habitat, outcompete native plant species, lower property values, and lead to public health concerns (McFarland et al. 2004).

Large-scale management techniques such as lake drawdowns, salvinia weevil (*Cyrtobagous salviniae* Calder and Sands) release, and mechanical harvesting are often implemented for giant salvinia management; however, aquatic herbicides are one of the most commonly used and effective management tools (Netherland 2014). Thousands of acres of giant salvinia are chemically managed annually, but management success is difficult to measure quantitatively. Treatment sites can encompass large areas, upward of 500 ha, and certain areas within these sites can be difficult to access or completely inaccessible by boat.

Large-scale applications often use spot assessments and visual injury rating scales as a method to quantify herbicide efficacy; however, these can be subjective and biased to the observer (Madsen and Bloomfield 1993). Numerous environmental factors including coastal tide movement, wind, precipitation, water flow, human interactions, and plant decomposition can also affect assumptions of successful or unsuccessful control. These factors make it difficult for managers to determine if plants remaining within treatment areas are the result of plant recovery or reinfestation from nontreated areas.

Currently, minimal effort has focused on monitoring herbicide efficacy, use patterns, and long-term control after operational management of giant salvinia. Widespread plant infestations, diminished funding, and limited trained personnel make it difficult to evaluate postherbicide application effectiveness. Although small-scale studies are beneficial and provide useful information regarding herbicide evaluations (Nelson et al. 2001, Mudge et al. 2016), additional monitoring tools need to be developed to determine if the best herbicides are being utilized in a field setting.

Remote sensing may be a potential monitoring method for assessing herbicide efficacy after field applications. It has

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become an important tool for wetland resource managers because of limited access and large expanses of aquatic ecosystems (Carter 1982). Remote sensing involves the use of one or more sensors mounted on various platforms (e.g., aircraft, satellite, unmanned aerial vehicles) that collect information based on the reflection of electromagnetic (EM) radiation from a particular area or object (Thorp and Tian 2004). The EM spectrum is composed of different forms of EM radiation that are grouped according to wavelength (Thorp and Tian 2004). For instance, the human eye detects red, green, and blue EM radiation in the visible spectrum, which ranges from 400 to 700 nm in wavelength; however, this is only a small percentage of the EM spectrum (Thorp and Tian 2004). Near-infrared (NIR) light (700 to 1,300 nm) makes up another portion of the spectrum and is considered a good indicator of vegetation health. Unfortunately this spectrum is not visible to the human eye (Thorp and Tian 2004).

Optical remote sensors have the ability to detect and quantify reflectance of EM radiation from vegetation, including that in the NIR region (Thorp and Tian 2004). In the visible region of the spectrum, green vegetation often displays very low reflectance and energy transmission because of energy absorption by photosynthetic and plant pigments (Chappelle et al. 1992). In contrast, reflectance and transmittance is typically high in the NIR spectral region (700 to 1,300 nm) because of minute absorption of energy by subcellular particles/pigments and scattering at the interfaces of mesophyll cell walls (Gausman 1974, Gausman 1977, Slaton et al. 2001).

The ability of a herbicide to alter the physiological condition of a plant is also assumed to alter the plant's spectral reflectance characteristics (Robles et al. 2010). Temporal herbicide injury and changes of energy reflectance have been documented in terrestrial plants (Adcock et al. 1990). However, little or no research is available that details changes of giant salvinia NIR reflectance in response to herbicide exposure. In aquatics, research has primarily focused on species differentiation (Best et al. 1981, Everitt et al. 2002, Jakubauskas et al. 2002, Everitt et al. 2008,), and success of biological control methods using reflectance data collected in the visible and NIR spectra (Everitt et al. 2005). Everitt et al. (2005) reported that moderate and severe feeding damage in plants infested with salvinia weevils during May and July had significantly lower NIR reflectance values in comparison with healthy plants. The mean NIR reflectance of giant salvinia with moderate feeding damage was reported as 16 ± 1.2 and 14.5 ± 0.09 in May and July, respectively (Everitt et al. 2005). Lower values of 9.5 ± 0.4 (May) and 10.3 ± 1.3 (July) were reported for plants with severe feeding damage (Everitt et al. 2005). In contrast, healthy plants in May and July documented a significantly higher mean NIR reflectance of 38.3 ± 2.6 and 35.7 ± 2.6, respectively (Everitt et al. 2005). In addition, Robles et al. (2010) documented that spectral data collected via a handheld spectroradiometer and transformed to simulate a Landsat 5 thematic mapper (TM) multispectral data set was capable of detecting and predicting herbicide injury on the floating aquatic plant water hyacinth [*Eichhornia crassipes* (Mart.) Solms].

It is important to note that the validation of satellite-acquired data requires the collection of ground-truth data to be used as a reference (Kharbouche et al. 2017). These data are often collected by *in situ* instrumentation (i.e., radiometers, spectrometers) either ground based, handheld, airborne, etc. (Kharbouche et al. 2017), or visual assessments by visiting predetermined sampling points within an area of interest. High-resolution multispectral satellite imagery and ground-truth sampling measurements have been used to successfully distinguish giant salvinia from mixed woody and mixed aquatic vegetation in large reservoirs (Everitt et al. 2008). Although this is very beneficial for natural-resource managers interested in mapping healthy giant salvinia infestations, management programs could be improved if a reliable low-cost monitoring protocol were established that could differentiate changes in plant health after large-scale control programs.

The goal of this research was to determine the applicability of using remote sensing to monitor and potentially predict control of giant salvinia treated with a combination of the aquatic registered herbicides glyphosate + diquat in a field scenario. Thus, the objectives of this study were to 1) investigate the relationship between visual percent control ratings of giant salvinia treated with glyphosate + diquat in Saline Lake, LA and NIR reflectance data acquired from Landsat 7 ETM+ and Landsat 8-OLI satellites, 2) investigate the relationship between NIR reflectance data collected from high-resolution WorldView-3 satellite imagery and percent giant salvinia control in a small-scale field application, 3) investigate the relationship between NIR reflectance data collected via drone with a low-cost NIR sensor payload and the percent giant salvinia control under controlled experimental conditions, and 4) develop a simple regression model from these data to predict and monitor giant salvinia control when exposed to glyphosate + diquat treatments.

MATERIALS AND METHODS

Saline Lake pilot study

Visual percent control of giant salvinia was evaluated using point-intercept surveys in Saline Lake, LA during the summer of 2015. Control ratings were recorded at specific points within a 20.2 ha^{-} plot of giant salvinia located on the northern shore of Chee Chee Bay in the southwestern portion of Saline Lake (Figure 1). Before surveying, giant salvinia within the plot was chemically managed on 2 to 4 July 2015. The treatment consisted of a foliar application of glyphosate[1] (3.3 kg ae ha^{-1}), diquat[2] (0.5 kg ai ha^{-1}), and two surfactants[3,4] (0.25 and 0.01% v/v, respectively). Pretreatment assessment on 1 July 2015 indicated that giant salvinia was healthy, mature, and actively growing throughout the plot. Posttreatment point-intercept surveys were conducted 2, 3, 6, and 10 wk after treatment (WAT). Surveys were conducted by navigating via boat to equally spaced (50 m) points created in ArcMap[5] 10.3® ArcGIS computer software (ESRI 2017) and recording visual percent control at each point. Percent control was determined in 10% increments where 0% = healthy plants/no control and 100% = complete

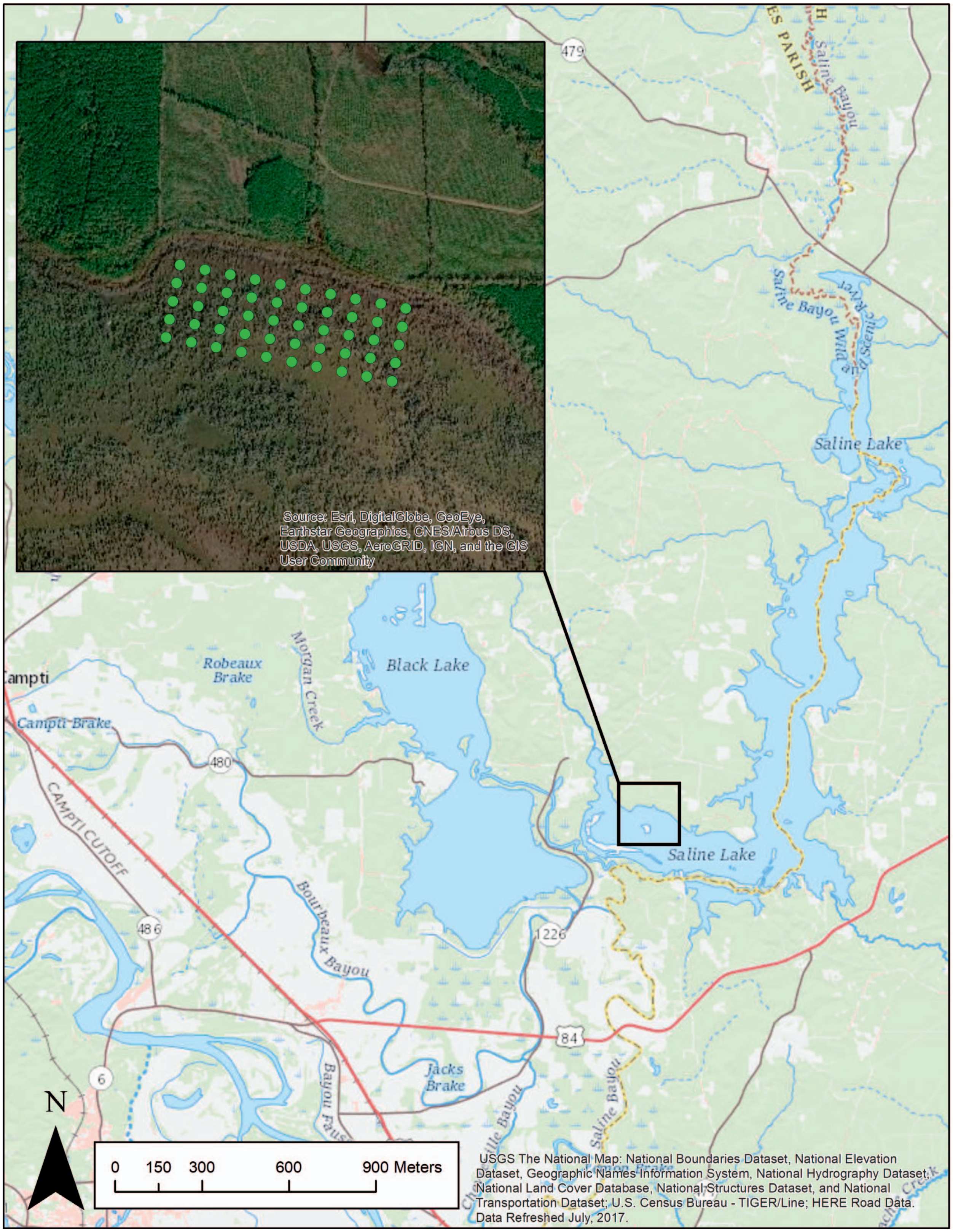

Figure 1. The 20.2 ha^{-1} point-intercept sampling plot on the northern shore of Chee Chee Bay in the southwestern portion of Saline Lake, LA. The points shown in the inserted image represent the locations visited during each survey to evaluate giant salvinia (*Salvinia molesta*) control after applications of the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and two surfactants (0.25 and 0.01% v/v, respectively).

Table 1. Point-intercept survey dates, number of weeks after treatment each survey was performed, the date of satellite imagery acquisition, and the corresponding sensor platform used to acquire remotely sensed data for Saline Lake, LA during the summer of 2015.

Survey Date	Weeks after Treatment (WAT)	Satellite Imagery Date	Sensor Platform
20 July 2015	2 WAT	23 July 2015	Landsat satellite 7 ETM
3 August 2015	3 WAT	31 July 2015	Landsat satellite 8 OLI TIRS
17 August 2015	6 WAT	16 August 2015	Landsat satellite 8 OLI TIRS
10 September 2015	10 WAT	17 September 2015	Landsat satellite 8 OLI TIRS

control/no plants present. Data were recorded electronically with a Trimble Yuma™[6] tablet computer and Farm Works® Farm Site Mate[7] software version 11.4 (Cox et al. 2011). A total of 50 points was visited during each survey.

Landsat-7 ETM+ and Landsat 8-OLI multispectral imagery data were acquired from the U.S. Geological Survey EarthExplorer image database. The Landsat-7 ETM+ and Landsat 8-OLI sensors are capable of measuring visible (450 to 690 and 433 to 680 nm, respectively) and NIR (770 to 900 and 845 to 885 nm, respectively) portions of the EM spectrum. Both Landsat platforms were used to get imagery that was most synchronous to the survey dates and imagery of the study site were acquired within 7 d of each point-intercept survey (Table 1). Previous work by Robles et al. (2010) indicated that the NIR band 4 from Landsat 5 TM consistently related phytotoxicity of herbicides to water hyacinth using a simple regression model; therefore, only NIR bands were used in the analysis. In addition, only NIR bands were utilized to create a more user-friendly model for a less experienced user. Each image was geometrically corrected and rectified to the World Geodetic Survey 1984 datum and universal transverse Mercator (zone 15 north) coordinate system. Landsat imagery was corrected to top of atmospheric (TOA) reflectance following the instructions listed in the Landsat 7 (USGS 1998) and Landsat 8 data user handbook (USGS 2016). Reflectance conversions of all Landsat data were performed using Earth resource data analysis system (ERDAS) Imagine®[8] software.

NIR reflectance values were extracted using ArcMap Spatial Analyst and averaged to determine the mean NIR reflectance for each 10% increment of visual percent control (Table 2). These data were subjected to a simple linear regression model relating percent visual control to NIR reflectance of giant salvinia using SigmaPlot®[9] version 11.0 statistical software. A total of 200 points was used in the analysis.

Table 2. Mean near-infrared (NIR) reflectance (± SE) and the total number of points recorded for each 10% control increment during point-intercept surveys after the application of the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) and diquat. (0.5 kg ai ha^{-1}) in 2015 at Saline Lake, LA.

Percent Control	NIR Reflectance (Mean ± SE)	No. of Points
0	0.2398 ± 0.051	93
10	0.1879 ± 0.011	7
20	0.1872 ± 0.014	10
30	0.1852 ± 0.009	11
40	0.1746 ± 0.009	15
50	0.1610 ± 0.007	23
60	0.1569 ± 0.007	14
70	0.1450 ± 0.013	14
80	0.1111 ± 0.013	9
90	0.0949 ± 0.000	1
100	0.1466 ± 0.011	3
		Total = 200

Small-pond study

A small-pond study was conducted during the summer of 2017 at the University of Louisiana Lafayette Cade Research Farm in Cade, LA. Four adjacent 0.10-ha^{-1} ponds, 0.3 to 0.6 m in depth, were utilized during the study (Figure 2). Each pond was inoculated with giant salvinia during the spring of 2017 and allowed to acclimate until plants achieved 100% coverage of the water surface. WorldView-3 imagery (1- to 1.5-m spatial resolution) of the study site was obtained from the commercial satellite imaging company DigitalGlobe™ through the NextView license agreement with the U.S. Army Engineer Research & Development Center (Vicksburg, MS). The WorldView-3 satellite is capable of measuring visible and NIR portions of the EM spectrum.

On 20 June 2017, three of the four ponds were treated with a tank mix of glyphosate (3.3 kg ae ha^{-1}), diquat (0.5 kg ai ha^{-1}), and surfactant[10] (0.25 % v/v) at a spray volume of 934 L ha^{-1}. Treatments were applied with a handheld spray gun attached to a Kappa[11] 55 diaphragm pump. The fourth pond was designated as a reference pond and not treated.

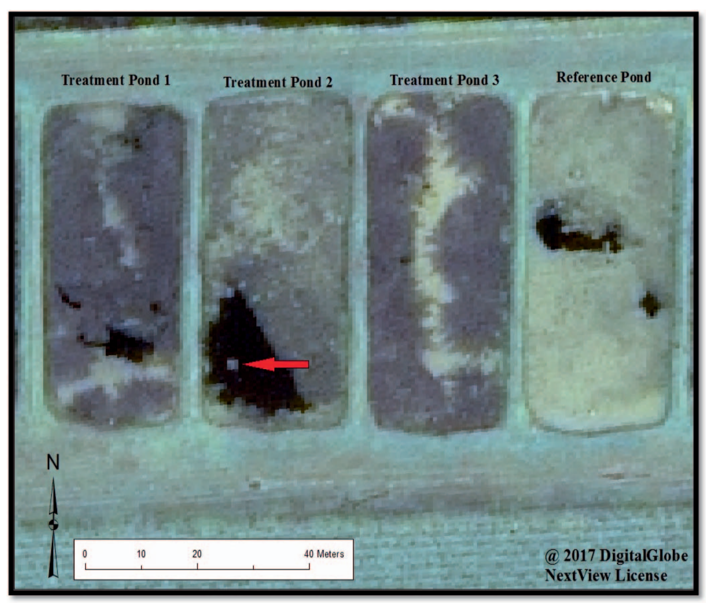

Figure 2. World View-3 true-color image of the four ponds utilized in the small-pond study at Cade, LA. Ponds were treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) on 20 June 2017. Imagery was acquired on 3 July 2017 (2 wk after treatment). The red arrow indicates a sampling plot in treatment pond 2 surrounded by open water.

Before treatment, eight 1.5 by 1.5 m plots, constructed of polyvinyl chloride (PVC) pipe, were placed within each pond. Plot area was determined on the basis of the spatial resolution of the WorldView-3 imagery. Plots were anchored to the substrate to prevent movement within ponds. Imagery was acquired on 3 July 2017 (2 WAT) and 28 July 2017 (6 WAT).

It was anticipated that imagery would be acquired a minimum of once every 2 wk; however, afternoon rain showers and cloudy conditions only allowed the acquisition of images at two time periods. Biomass was harvested at 2 WAT and 6 WAT from multiple PVC plots throughout each pond, transported back to Louisiana State University (LSU), dried (65 C) to a constant weight, and percent giant salvinia control was determined by the comparison of biomass in treated plots with biomass in reference plots using the following equation: (reference biomass − treatment biomass)/reference biomass × 100 = % control.

WorldView-3 imagery was geometrically corrected to control points using ground measurements and visual targets to ensure the accuracy and location of each plot within the sampled ponds. Multispectral data were processed and corrected to TOA reflectance in ERDAS Imagine software following the user guidelines provided by DigitalGlobe (Kuester 2016). For each sampling period, NIR reflectance and percent control data of each harvested plot were subjected to a simple linear regression ($y = a - bx$) using SigmaPlotsion 11.0 statistical software.

Mesocosm study

On 23 August 2017, giant salvinia was planted at the LSU Aquaculture Research Facility (Baton Rouge, LA) into 30 (76-L) plastic containers (49.5 cm diameter by 58.4 cm height) filled with approximately 60 L of pond water (pH 8.5) and amended with 14 g of sphagnum moss to lower the pH to < 7.0. In addition, 2.1 g of Miracle-Gro®[12] water-soluble lawn food (24–8–16) was applied to each container at planting and every 2 wk throughout the 8-wk study. Plants were allowed approximately 14 d to acclimate to experimental conditions. Plants were healthy, actively growing, and were beginning to form multiple layers at the conclusion of the 2-wk acclimation period. Plants in 25 of the 30 tanks were treated with the same herbicide combination utilized in the small-pond study, with the remaining 5 designated as reference tanks. Biomass was collected from 5 of the 30 tanks at 2, 4, 6, and 8 WAT. Reference tanks and the remaining five treated tanks were harvested at the conclusion of the 8-wk study. All harvested biomass was dried (65 C), weighed, and percent control was determined using the same methods as in the small-pond study.

Imagery of the study area was collected via a DJI Phantom™[13] drone equipped with a low-cost Sentera[14] Single Sensor™ capable of capturing images in 575- to 1,050-nm wavelengths (e.g., green to NIR) of the EM spectrum. AgVault™[15] data management software was utilized for autonomous flight control, image acquisition, and mosaicking of acquired images. Images of the study area were acquired before biomass collection on cloudless days between 11:00 A.M. and 12:00 noon at a flight altitude of 18.3 m with 80% image overlap. Reflectance targets were placed within the study area and used to calibrate sensor reflectance on the basis of values previously generated using a FieldSpec3®[16] spectroradiometer during appropriate solar and weather windows. Image analysis was performed in ArcMap by overlaying a 0.10-m-radius polygon feature in the center of each tank, followed by the conversion of each raster image pixel inside the polygon to individual points containing reflectance values using ArcMap Spatial Analyst tools. Polygons were placed in the center of each tank to avoid shadowing or edge effects that may affect pixel values (Figure 3).

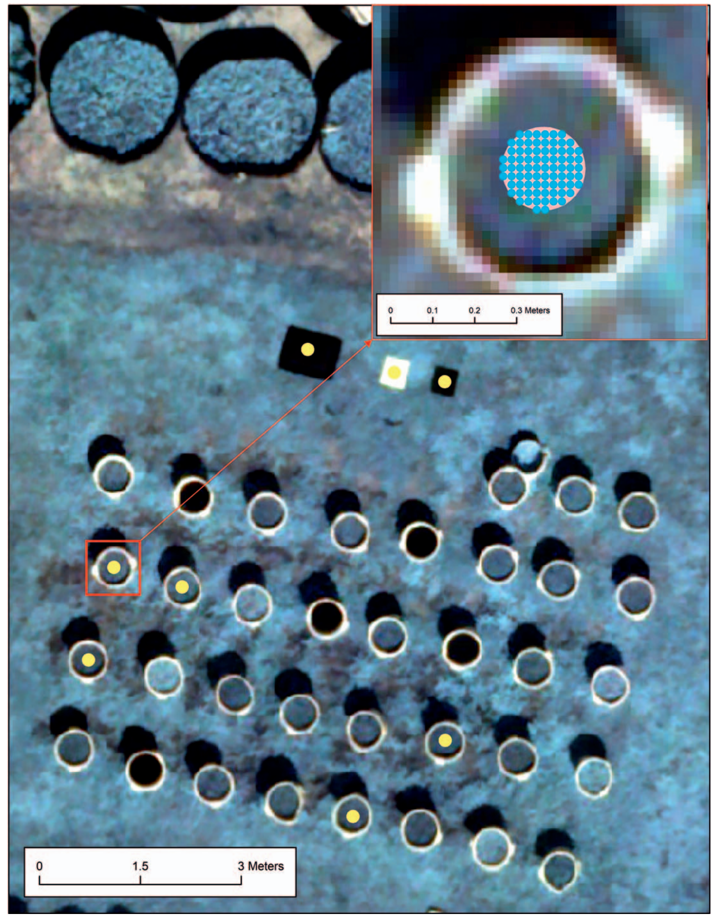

Figure 3. Imagery of giant salvinia (*Salvinia molesta*) treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) at the Louisiana State University Aquaculture Research Facility in Baton Rouge, LA. Imagery was collected with a DJI Phantom drone and Sentera Single Sensor payload on 5 October 2017 (4 wk after treatment). Polygons (0.10-m radius) inside the tanks represent the area used for calculating the average near-infrared (NIR) reflectance of each mesocosm tank. Raster pixels intersecting each tank polygon were converted to points as seen in the inserted image. NIR reflectance data associated with each point were used to calculate the average NIR reflectance within each tank.

This process converts individual pixels of the image to individual points containing the reflectance values for each respective point. The number of points within each tank polygon ranged between 79 and 81. A spatial join was then performed to create a new polygon feature class containing the average reflectance values of each polygon within each tank. NIR reflectance and percent control data were subjected to a simple linear regression using SigmaPlot version 11.0 statistical software. The resulting regression equation was then used in conjunction with NIR reflectance values collected during the small-pond study at 6 WAT to predict giant salvinia percent control. The predicted percent control values were then compared with the observed percent control values established in the small-pond study at 6 WAT.

RESULTS AND DISCUSSION

Saline Lake pilot study

NIR reflectance of chemically managed giant salvinia and visual percent control ratings in Saline Lake, LA were significant and negatively correlated ($R^2 = -0.785$) (Figure 4); thus control decreased as reflectance increased. These data are comparable with Robles et al. (2010), who documented the same response between band 4 (NIR) of Landsat 5 TM and phytotoxicity ratings of water hyacinth treated with glyphosate and imazapyr. Although visual observations and reflectance data documented a negative linear relationship of $R^2 = -0.785$, factors such as sample size, spatial resolution, plant movement, and other co-occurring species likely had an impact on the analysis.

A total of 200 visual observations was used in the analysis, but the number of observations for each percent control increment was not equal. For instance, only three observations documented 100% plant control compared with 23 observations documenting 50% control (Table 2). Although satellite imagery was collected within 7 d of each survey, it was not synchronous for the day of surveys. The small number of samples with 100% control ($n = 3$) and the ability of giant salvinia to move into areas that were essentially "open water" between surveying and image collection most likely contributed to the higher average reflectance of the 100% control ratings than that observed for 80 and 90% control. In addition, considerable amounts of healthy bald cypress [*Taxodium distichum* (L.) Rich.] trees were present throughout the sampling plot. Bald cypress, combined with the low spatial resolution of multispectral Landsat images (i.e., 30 m), likely had an impact on the true NIR reflectance of giant salvinia within the plot. Despite these limitations, there was a clear distinction between the NIR reflectance of injured and noninjured plants. The availability of Landsat data at no cost makes this technology useful for monitoring management success of giant salvinia in a large-scale field scenario. These results increased the expectations of the applicability of this study; however, it was hypothesized that precision could be improved if tested on a smaller scale.

Small-pond study

Percent control and NIR reflectance of giant salvinia in sampled plots were significantly correlated at 2 and 6 WAT, with $P = 0.047$ and $P < 0.0001$, respectively. Data collected 6 WAT was more representative of actual percent control and documented a stronger negative linear relationship ($R^2 = -0.843$) compared with 2-WAT data ($R^2 = -0.579$) (Figure 5). The low rate of diquat (0.5 kg ai ha^{-1}) in combination with glyphosate (3.3 kg ae ha^{-1}) likely influenced the 2-WAT data. Diquat is a fast-acting contact herbicide that leads to rapid wilting and desiccation several hours after application and complete foliar necrosis in 1 to 3 d (Senseman 2007). Because diquat provides rapid visual injury a few hours after application, it is commonly used as a marker to distinguish treated versus nontreated sites (Mudge and Netherland 2014). The low rate of diquat likely resulted in a NIR reflectance value not representative of actual percent control at 2 WAT.

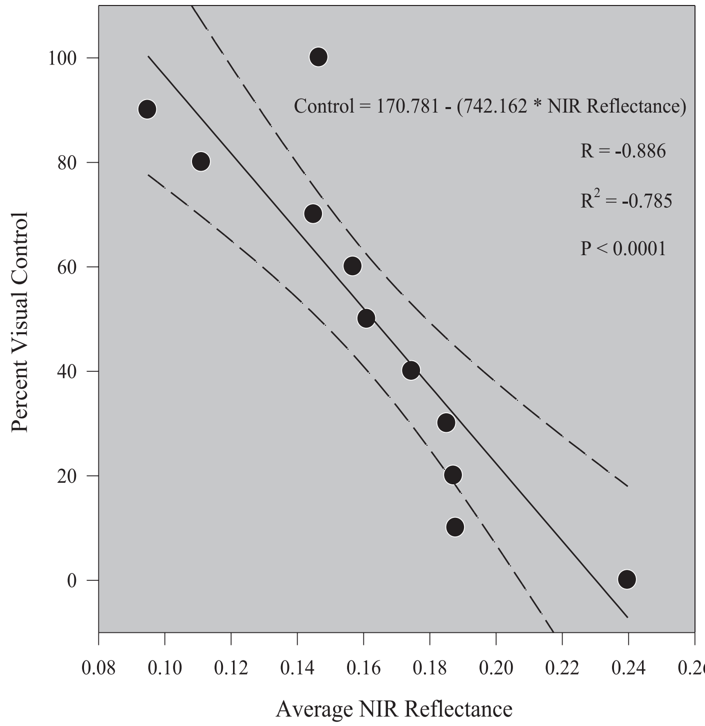

Figure 4. Linear relationship of visual control ratings for giant salvinia (*Salvinia molesta*) treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) at Saline Lake, LA, and near-infrared (NIR) reflectance values acquired from Landsat 7 and Landsat 8 satellite platforms. Visual ratings were collected at 2, 3, 6, and 10 wk after treatment. Point values represent the average NIR reflectance for each 10% visual control rating increment (0 to 100 scale). The solid black line represents the regression line and dashed lines represent regression line 95% confidence intervals.

Sampling at 6 WAT allowed ample time for treated plants to become necrotic and degrade, thus providing a stronger negative linear relationship between giant salvinia NIR reflectance and percent control within sampling plots. These data are contrasting to those of Robles et al. (2010) that documented the strongest linear relationship between phytotoxicity and reflectance of water hyacinth 2 WAT when treated with glyphosate and imazapyr. Contrasting results are most likely due to herbicide rate, species being tested, and experimental design. The current study was implemented to simulate a field-based application, as opposed to a controlled mesocosm experiment where complete herbicide-to-plant contact is easily attainable. In

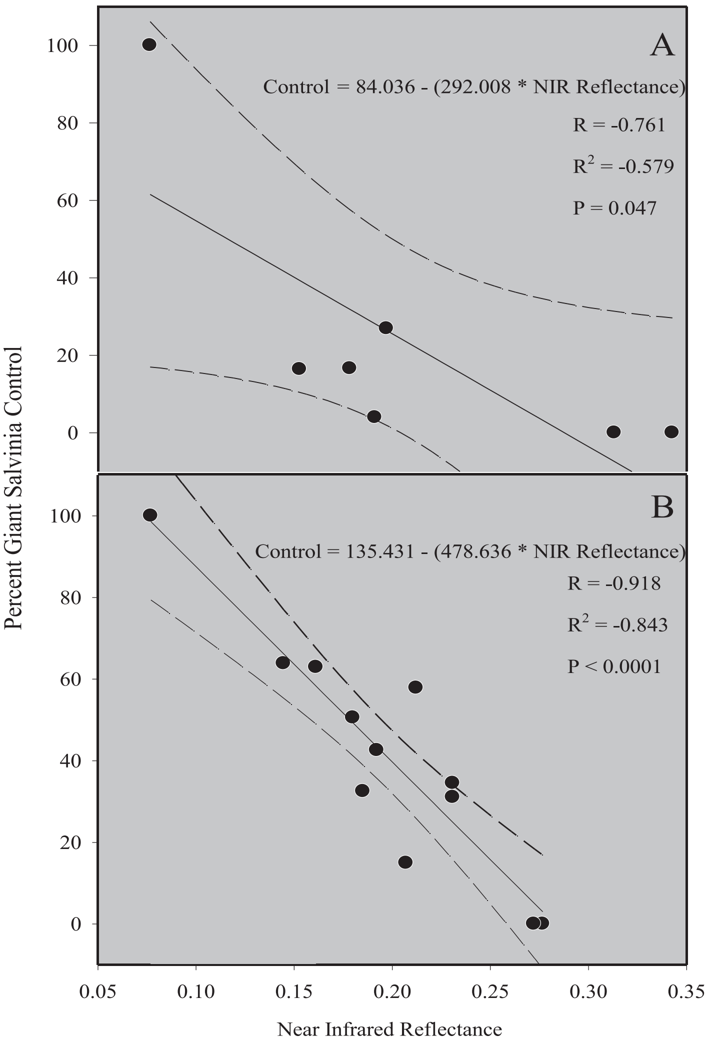

Figure 5. Linear relationship between percent control of giant salvinia (*Salvinia molesta*) treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) on 20 June 2017 at Cade, LA, and the near-infrared (NIR) reflectance values acquired from WorldView-3 satellite imagery on A) 3 July 2017 (2 wk after treatment) and B) 28 July 2017 (6 wk after treatment). Point values represent percent control of giant salvinia and NIR reflectance values within sampled plots. The solid black line represents the regression line and dashed lines represent 95% confidence intervals of the regression line.

addition, the current study utilized biomass data, as opposed to visual phytotoxicity ratings.

Mesocosm study

Data collected from the 8-wk mesocosm study documented a strong negative linear relationship ($R^2 = -0.914$) between percent control and NIR reflectance values of giant salvinia (Figure 6). Because the strongest relationship between percent giant salvinia control and NIR reflectance was documented during this study, the resulting linear regression equation was used to predict percent control values utilizing data collected during the small-pond study. The predicted control values were plotted against observed control values to examine the relationship. The following

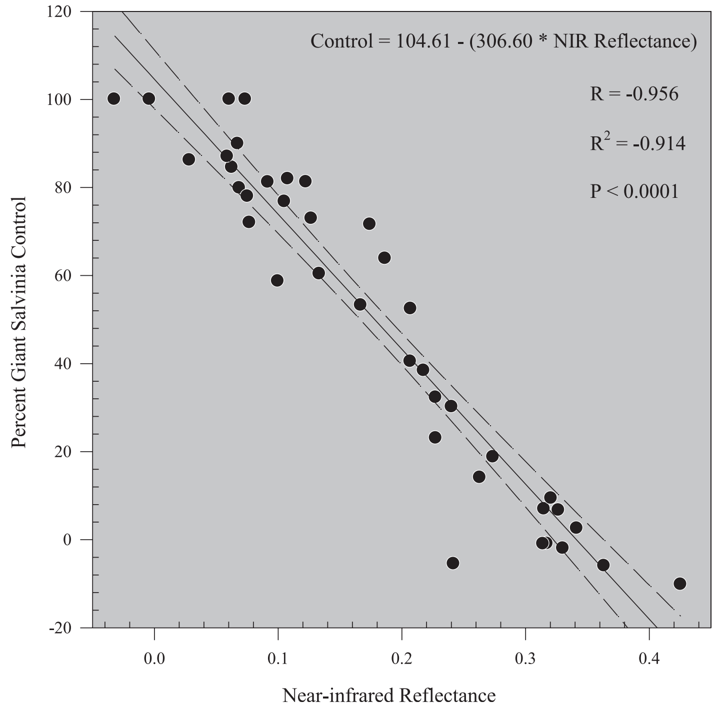

Figure 6. Linear relationship between percent control of giant salvinia (*Salvinia molesta*) treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) on 7 September 2017 and near-infrared (NIR) reflectance values collected during the mesocosm trial at Baton Rouge, LA. Point values represent percent control established from collected biomass data and NIR reflectance values acquired from a DJI Phantom drone equipped with a Sentera Single Sensor. The solid black line represents the regression line and dashed lines represent 95% confidence intervals of the regression line.

formula, also depicted in Figure 6, was used to predict percent control values: predicted percent control = 104.61 − (306.60 × NIR reflectance). The relationship between predicted and observed percent control values was linear and significant ($P \leq 0.0001$), yielding R and R^2 values of 0.918 and 0.843, respectively (Figure 7). Data in all three studies documented a negative linear relationship; thus it is clear that as herbicide control increases, NIR reflectance of the plant canopy decreases. A similar response was documented by Everitt et al. (2005), who documented decreased NIR reflectance values as giant salvinia damage increased in response to the biological control agent salvinia weevil. Everitt et al. (2005) also documented NIR reflectance values of healthy, moderate, and severely damaged giant salvinia to be 35.7 ± 7, 14.5 ± 0.9, and 10.3 ± 1.3, respectively, which are comparable with the results reported in the current mesocosm study that documented 0, 50, and 75% control to correspond to a NIR reflectance of 34.1, 17.9, and 9.7, respectively.

Results from these data indicate that it is possible to predict and monitor percent giant salvinia control within treatment areas. On the basis of the NIR spectral response of giant salvinia to herbicide applications, remote sensing can provide beneficial information on the success of large-scale herbicide applications. Estimations of percent control can be determined by using NIR values of a remotely sensed

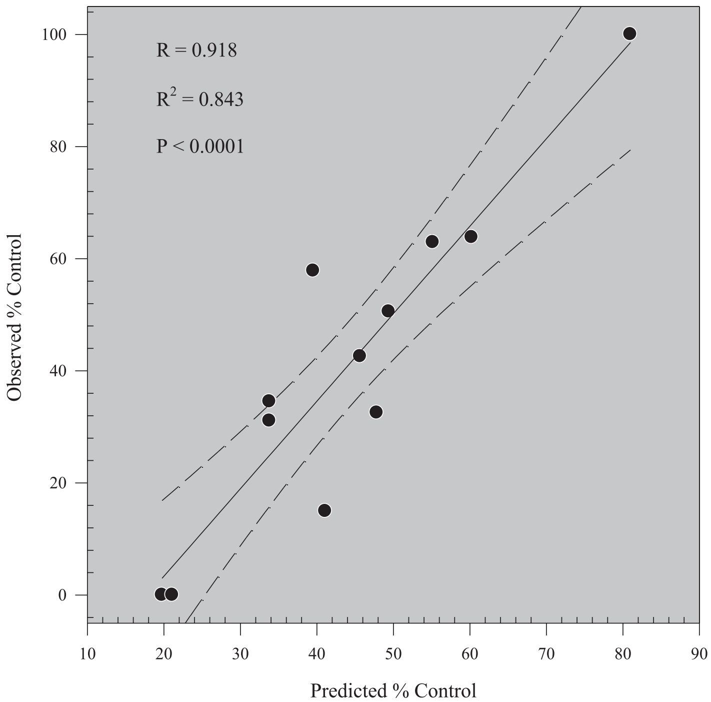

Figure 7. Linear relationship between observed percent control and predicted percent control of giant salvinia (*Salvinia molesta*) treated with the aquatic herbicides glyphosate (3.3 kg ae ha^{-1}) + diquat (0.5 kg ai ha^{-1}) and surfactant (0.25% v/v) 6 wk after treatment at Cade, LA. Predicted percent control values represent the estimated percent control using near-infrared reflectance data from Worldview-3 imagery and the linear regression equation in Figure 6. The solid black line represents the regression line and dashed lines represent 95% confidence intervals of the regression line.

image and the aforementioned equation. Increases or decreases in predicted control values and differentiation between treated and nontreated plants within an area will provide natural resource managers with critical information about the success of a treatment, potential plant recovery or reinfestation, and the total amount of acreage treated. Future research should evaluate the accuracy of the prediction model on a larger scale and its precision with data collected from other NIR sensors. In addition, research investigating additional spectral bands and/or band combinations may provide more information for monitoring aquatic plant management operations.

SOURCES OF MATERIALS

[1]Roundup Custom™, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.

[2]Tribune™, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 24719.

[3]Aqua-King Plus®, Winfield Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164.

[4]AirCover™, Winfield Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164.

[5]Environmental Systems Research Institute, ArcMap® 10.3, ArcGIS Desktop, Redlands, CA.

[6]Yuma™, Trimble, Sunnyvale, CA.

[7]Farm Works®, Farm Site Mate 11.4, Hamilton, IN.

[8]ERDAS, ERDAS® Imagine 2015, Hexagon GeoSpatial, Peachtree Corners Circle, Norcross, GA.

[9]Sigma Plot® Version 11.0, Systat Software Inc., San Jose, CA 95131.

[10]Turbulence™, Winfield Solutions LLC, P.O. Box 64589, St. Paul, MN 55164.

[11]Kappa-55 diaphragm pump, UDOR U.S.A, Inc., 500 Apollo Dr., Lino Lakes, MN 55014.

[12]Miracle Gro® All Purpose Plant Food, The Scotts Company LLC, P.O. Box 606, Marysville, OH 43040.

[13]DJI Phantom 3™, SZ DJI Technology Co. Ltd., Shenzhen, China.

[14]Sentera Single Sensor™, Sentera LLC, 6636 Cedar Ave. South, Suite 250, Minneapolis, MN 55423.

[15]AgVault™ Software, Sentera LLC, 6636 Cedar Ave. South, Suite 250, Minneapolis, MN 55423.

[16]FieldSpec® 3, Analytical Spectral Devices Inc. (ASD), 2555 5th St., Suite 100, Boulder, CO 80301.

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