MONITORING YELLOW FLOATING HEART (*NYMPHOIDES PELTATA*) ON LAKE CARL BLACKWELL VIA REMOTE SENSING

By

STEPHEN ANGLE

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MONITORING YELLOW FLOATING HEART (*NYMPHOIDES PELTATA*) ON LAKE CARL BLACKWELL VIA REMOTE SENSING

Thesis Approved:

Dr. Scott Stoodley

Thesis Adviser

Dr. Andy Dzialowski

Dr. Jamey Jacob

ACKNOWLEDGEMENTS

Dr. Adam Mathews

Abby McCrea

Victoria Natalie

Name: STEPHEN ANGLE

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Abstract: Yellow floating heart (*Nymphoides peltata)* is an invasive floating-leaf aquatic plant. This species forms dense mats of rhizomatous vegetation that can produce tens of thousands of seeds per square meter. These seeds spread via hydrochory and establish additional colonies. Fragmentation of *N. peltata* from disturbances further increases its spatial extent, as detached plant material forms new colonies. *N. peltata* successfully colonized over 40 acres on Lake Carl Blackwell, in Stillwater, Oklahoma. The herbicide glyphosate was applied on 10 dates in 2018 to combat further spread of *N. peltata.* To evaluate the efficacy of these spraying events, a DJI Phantom 4 Unmanned Aerial Vehicle (UAV) was used to image the spatial extent of *N. peltata* coverage of infested coves on five dates over the 2018 growing season. These images were used to create orthomosaics and subsequently analyzed to examine temporal changes in plant coverage spatial extent in response to glyphosate treatment. Near infrared (NIR) images from the Sentinel-2 satellite were also used to evaluate plant health based on Normalized Difference Vegetation Index (NDVI). A pilot study evaluated the spatial extent and NDVI changes of one infested cove on the north side of Lake Carl Blackwell. This study includes and is an expansion of that pilot study where five additional coves were analyzed, and comparisons were made between UAV and Sentinel-2 NDVI results at different NDVI thresholds for plant health (0.33, 0.365, and 0.4). A brief project cost comparison between monitoring methods is included. Results show limited success with glyphosate application, as *N. peltata* maintains a strong presence in five of the six study coves. This study presents an effective methodology for monitoring plant stress temporally using UAV and satellite remote sensing.

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CHAPTER I

INTRODUCTION

Damages associated with invasive plant and animal species are among the largest challenges faced by natural resource managers. The annual cost of remediation and loss of ecosystem services from invasive species is over $130 billion in the United States alone (Huang & Asner, 2009). According to the Environmental Protection Agency (EPA, 2005), $100 million per year goes directly into the control of aquatic invasive plants (Lovell and Stone, 2005). These plants decrease the biodiversity of native systems and impede recreation.

Yellow floating heart (*Nymphoides peltata*) is an invasive freshwater aquatic plant species that closely resembles the water lily. The species produces brightly-colored yellow flowers and heart-shaped floating leaves (Nault & Mikulyuk, 2009). At peak season, this plant forms dense mats of vegetation that outcompete native vegetation and impede recreation. *N. peltata* fragments (stolons, leaves, rhizomes, etc.) that become separated from the parent plant can take root elsewhere and form new colonies. For this reason, large-scale mechanical removal of this species is impractical and potentially counterproductive to eradication. Chemical removal via herbicide is a potentially viable option for *N. peltata* eradication.

N. peltata has been found on Lake Carl Blackwell located west of Stillwater, Oklahoma. Patches of *N. peltata* have been on the lake as early as April 2008 in northern coves based on visual assessment if Google Earth images, but with no ground truth data to verify. This infestation appears to have moved from a single northern cove to several coves across the lake beginning in 2015 based on temporal assessment of satellite imagery from 2008-present (Google Earth). *N. peltata* range has continued to spread since 2015, particularly in the lake's northern coves, to approximately 50 acres of coverage. The herbicide glyphosate was applied to the infestations over the 2017 and 2018 growing seasons. Glyphosate proved to be an effective *N. peltata* control measure in southern coves on Lake Carl Blackwell when applied over the 2017 growing season (Koenig 2018). Control via glyphosate was comparatively less effective in 2018 in the lake's northern coves.

N. peltata mats have continued to spatially expand in most northern coves of Lake Carl Blackwell post-treatment. Though glyphosate application has had some observable stress effects on *N. peltata* vegetation, neither change in spatial coverage nor damage to plant tissue has been quantified. A low-cost, effective remote sensing methodology is needed to track the efficacy of the treatment. This study utilized both unmanned aerial vehicle (UAV) and Sentinel-2 satellite imagery to investigate temporal changes in the health and spatial extent of *N. peltata* on Lake Carl Blackwell throughout the 2018 growing season. This research analyzed imagery data from six northern coves and is based on a previous pilot study of one northern cove, termed Cove D.

The objectives of this study are as follows:

1. Estimate total *N. peltata* extent of the study sites measured in acres;

2. Measure the change in acreage spatial extent (e.g., spread and/or reduction) of *N. peltata* coverage in study sites during the 2018 growing season during herbicide treatment; and

3. Determine relative plant health using Normalized Difference Vegetation Index (NDVI).

CHAPTER II

LITERATURE REVIEW

Nymphoides peltata Physiology and Impact

N. peltata forms dense mats of stolons, leaves, and adventitious roots in the air/water interface of slow-moving systems like lakes and ponds. These mats produce an average of 180 fruits/m^2, each containing between 40-80 seeds (Nault & Mikulyuk, 2009). *N. peltata* seeds are hydrophobic, 4-5 mm in length, and feature fringed margins. These fringes allow seeds to hitchhike on the feathers and feet of foraging waterfowl, aquatic mammals, deer, and livestock. The plant is subsequently introduced to other lakes and ponds by these vectors (Cook 1990). *N. peltata* seeds spread locally by forming chains and dispersing across the water's surface.

One genetic study by Larson (2007) supported vegetative propagation as the dominant dispersal method relative to sexual reproduction. The versatile reproduction characteristics of *N. peltata* make it difficult to eradicate in climatologically viable areas with little natural predation or competition. *N. peltata* emerges in the spring and recedes typically around October in the northern hemisphere. Peak reproduction occurs during the summer months (Nault & Mikulyuk, 2009).

During the growing season months, thick vegetative mats of *N. peltata* impede recreation and lake navigability by inundating entire lake coves. Similar to *Salvinia molesta,* a more highly-studied aquatic nuisance species, *N. peltata* has the potential to decrease dissolved oxygen (DO) availability by interfering and altering the water/atmosphere interface. It also alters DO through large-scale decomposition in the water column at the end of the growing season (Fairchild et al., 2002; Nault & Mikulyuk, 2009). Lake Carl Blackwell is a man-made reservoir and is thus an ecologically altered system. Eradication of *N. peltata* on Lake Carl Blackwell is nonetheless still imperative to protect the lake and surrounding water bodies as recreational, aesthetic, and potable water resources.

Past Spread and Invasion Risks

N. peltata, unlike other *Nymphoides* species, is highly invasive in several countries including Ireland, Sweden, New Zealand, and the United States (Nault & Mikulyuk, 2009; Gren et al, 2009). *N. peltata* favors the temperate climate of its native Eurasian/Mediterranean range. It presents a potential threat in many non-native temperate areas. The United States Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS) conducted a Weed Risk Assessment that estimated 47% of the U.S., mainly located in the eastern half of the country, as climatologically viable for *N. peltata* establishment (USDA APHIS, 2012). This report found high spread and impact potential for *N. peltata* based on historically invasive behavior. Lake Carl Blackwell's well-established *N. peltata* population must be systematically and efficiently eradicated in order to protect water bodies throughout the State of Oklahoma from invasion.

Glyphosate Description

Glyphosate is an herbicide that has been widely used for aquatic plant control in the United States since 1977 (Getsinger et. al, 2008). It kills plants indiscriminately by way of shikimic acid pathway disruption that deprives plants of essential enzymes for protein synthesis (Henderson et al., 2010).

Glyphosate has been studied extensively and found to be 90% effective in killing an herbaceous terrestrial weed Merremia (*Merremia peltata)*. It outcompeted four other herbicide mixtures during this study (Balasubramaniam & Wijayanto, 2015). Glyphosate studied at eight concentrations on macrophytes in a greenhouse environment yielded between 40% (480 g per ha) and 100% (3840 g per ha) efficacy using .5% AterBane surfactant. *Eichhornia crassipes, Pistia stratiotes, Salvinia molesta, Salvinia herzogii*, and *Urochloa subquadripara* were all successfully eradicated at the highest tested glyphosate dosage (Cruz et al. 2015). A similar study testing glyphosate in different concentrations and surfactant combinations applied to *Salvinia molesta* found a direct relationship between degree of control and glyphosate concentration. Solutions between 0.45% and 3.64% glyphosate were tested over 42 days in a mesocosm study. Significant control was observed at all concentrations (Fairchild et al., 2002). For these reasons, aquatic application of glyphosate at .75% is a theoretically sound management strategy for the control of *N. peltata* on Lake Carl Blackwell.

Challenges with Aquatic Glyphosate

Aquatic use of glyphosate via Rodeo Aquatic Herbicide requires mixing a specific concentration of the chemical with a surfactant and applying directly to the plant material. The target plant must be photosynthetically active and the herbicide must have sufficient contact time with plant tissue before dilution in order to be effective (Getsinger et al., 2008; Wallace et al. 2016). This presents a problem for aquatic plant control, particularly when the target vegetation is floating as opposed to emergent. Glyphosate takes anywhere from 4 to 20 days to kill plant tissue beyond recovery (Henderson et al., 2010). Rainfall, wind, waves, and currents can shorten glyphosate contact time with floating leaves. These factors can potentially limit the practicality and efficacy of glyphosate use in a lake environment. Remote sensing of the *N. peltata* eradication process on Lake Carl Blackwell can provide insight as to the effectiveness of glyphosate applications.

Remote Sensing of Invasive Plants

Recent studies include the use of Unmanned Aerial Vehicle (UAV) photography, manned aerial photography, and satellite remote sensing of invasive species within a defined area. Much of the current research in invasive species monitoring focuses on invasive plant detection rather than herbicide efficacy. The spatial, spectral, and phenological characteristics of invasive plants are mapped and evaluated for accuracy (Bradley, 2014; Hill et al., 2017; Huang & Asner, 2009; Mullerova et al., 2013; Mullerova et al., 2017; Somodi et al., 2012). Remote sensing methods have been compared in these studies based on accuracy and resource expenditure for analysis.

Previous studies have focused largely on the effectiveness of collection and processing methods relative to their cost. Satellites such as Hyperion have been used to accurately identify invasive species at 80% or greater accuracy and at much lower costs than airborne imagery collection (Huang and Asner, 2009). Recent developments in the remote sensing field have increased the accessibility and applicability of remote sensing in invasive species management for stakeholders. Both UAV and satellite imagery can be utilized to map invasive plant species at 85-90% accuracy, reducing costs associated with traditional airborne imagery and field studies (Adgee et. al., 2015; Martin et al. 2018). Lake Carl Blackwell is an ideal site for a water resource management study that utilizes similar remote sensing equipment and analyses for invasive species monitoring, particularly regarding herbicide efficacy.

Data collection for invasive species monitoring can be done quickly and relatively easily via UAV. This imagery can be subsequently processed and analyzed for spatial extent monitoring (Hill et al, 2017). Alternatively, satellite imagery can be downloaded from GIS clearinghouses for the same purpose (Somodi et al., 2012; Mullerova et al., 2017). Knowledge of the study area and required image resolution is essential to determining which data collection platform to use. The spatial resolution of data should complement the size and scale of the study site in order to effectively monitor changes in invasive plant coverage (Martin et al., 2018). Invasive species monitoring can be conducted effectively through UAV and satellite imagery depending on the size and distribution pattern of invasives, as well as the presence or absence of canopy (Martin et al., 2018; Zhou et al. 2018; Mullerova et al., 2017). Resource managers should consider the spatial extent and distribution of invasive plant presence when determining which remote sensing platform to use.

Floating *N. peltata* mats on Lake Carl Blackwell's northern coves are each several acres in area with very little canopy cover to obstruct detection. The areas of these infested coves are small enough for effective UAV imaging, yet large enough that 10-meter resolution satellite imaging is sufficient for plant health calculations. The spatial extent, homogeneity, and visibility of these mats provide the opportunity for both UAV and satellite detection of *N. peltata*.

Studies have shown high levels of success in mapping invasive species accurately by using time-series analysis (Liu et al. 2017; Pastick et al. 2018). This is due in large part to phenology, or seasonal change. The spectral signatures of plants change as they progress through their life cycles. This allows for easier discernment between different plant species both by manual digitization and computer algorithm classification (Ouyang et al. 2013; Bradley 2014; Wallace et al. 2016; Liu et al. 2017). *N. peltata* develops fringed, bright yellow flowers visible with high spatial resolution imagery when sexually mature.

The bright yellow flowers produced by *N. peltata* are one example of a useful phenological trait used for spectral separation from other species. These flowers are between 2-4 cm in diameter, making approximately 2 cm UAV resolution sufficient for imaging at multiple pixels per flower (Illinois-Indiana Sea Grant, 2019). This specific phenological response can be utilized for delineating *N. peltata* from sparse patches of native plants such as American lotus (*Nelumbo nutia)* and American pondweed (*Potamogeton nodosus*) on Lake Carl Blackwell.

UAV Imaging and Processing

Very high resolution (cm) data is ideal for imaging phenological details at small scale sites. Phenological traits such as small flowers can be detected at this resolution and used to differentiate a target plant from surrounding vegetation. Hill et al. (2017) used a DJI Phantom 3 UAV to acquire red, green, blue (RGB) data at a resolution of 2.26 cm monitoring Yellow flag iris (*Iris pseudacorus*) on two lakes in Canada. Over 2,600 photos were taken at these two lakes and subsequently mosaicked into orthophotos for analysis. Hill et al. (2017) suggested that UAV imagery was more accurate for plant detection than more traditional field methods. The northern coves of Lake Carl Blackwell are ideal sites to apply the methods of spatial extent estimation utilized by Hill et al. (2017) due to similarities in hardware and software availability, site environments, and target species.

Multiple software packages and methods of analysis exist for analyzing image sets for invasive species monitoring. Unlike some downloaded satellite data from GIS clearinghouses, UAV image collections require pre-processing. Orthomosaics must be created before analysis can be completed. The software packages Pix4D and Agisoft PhotoScan were used by Hill et al. (2017) and Mullerova et al. (2017) in order to accomplish this task. Martin et al. (2018) used the Structure from Motion algorithm in Agisoft PhotoScan to generate orthophotos from imagery sets. This computer vision algorithm uses texture within imagery to create point clouds, which can then be used to create orthomosaics.

Though the Structure from Motion algorithm is computationally complex, the Agisoft PhotoScan Professional software package is capable of producing point clouds from hundreds of photos. The spatial extent of Lake Carl Blackwell coves are such that 2 cm resolution imagery can be collected using less than 1000 photos at each site. For this reason, Agisoft PhotoScan is capable of effectively processing imagery for this study by means of orthophoto creation over a reasonable amount of time. Orthophotos typically need between 3 and 10 hours to process depending on the number of photos in a given set.

Manual vs. Computer-Based Classification

Some analyses in recent invasive species literature focuses on computer algorithm classification (Hill et al. 2017; Mullerova et al. 2013; Mullerova et al. 2017; Somodi et al., 2012). Supervised pixel-based analysis involves user input or training of the algorithm by way of positive and negative training points or classes (Hill et al., 2017; Mullerova et al., 2013; Mullerova et al., 2017; Somodi et al., 2012). Pixel-based classification can automate the analysis process when properly executed, saving user time over large data sets.

Supervised computer-based classification can require more user time than manual classification when classifying small study sites. Computer misclassification has occurred at higher rates than human classification error in some studies (Bradley, 2014; Hill et al., 2017). This is due in large part to low spectral resolution, even when spatial resolution remains high. More spectral bands tend to facilitate a more accurate decision-tree model. RGB data alone can be used for algorithm-based analysis, though multi- and hyperspectral data typically produces more accurate classification results (Hill et al., 2017). Available RGB images from Lake Carl Blackwell's northern coves are better suited to manual classification for estimating *N. peltata* spatial extent. This is due in part to the low spectral capacity of the images. Manual classification also allows flexibility in adding/subtracting areas of coverage between imagery dates as needed for orthophotos with small portions of missing *N. peltata* spatial extent, as was necessary in the larger coves.

The presence of sun glare in imagery gives an additional advantage to manual classification. Glare is problematic for algorithm classification, whereas a manual classifier can identify glare-obscured areas and use visual context to correct for them. Many orthomosaics in this study contain glare, as UAV image capture took place throughout the summer months on Lake Carl Blackwell and at varying times.

Hand digitization of invasive species presence in a GIS environment is an applicable method when using imagery with adequate spatial resolution. Hill et al. (2017) found manual classification to be the most accurate and cost-efficient method of analysis between manual, pixel-based, and field survey. Manual classification, while slower over larger and more species-rich data sets, is well suited for identifying large patches of a single species. *N. peltata* dominates large homogenous patches of Lake Carl Blackwell coves, making manual classification ideal. Results of these spatial extent estimations can then be used to spectrally evaluate *N. peltata* health using Sentinel-2 imagery.

Sentinel-2 Satellite Imagery

The Sentinel-2 mission launched in 2015 comprises two satellites that capture 290 km swaths for the European Space Agency (ESA). These satellites work in tandem to provide spectral information at return rates as high as 5 days. The satellites capture 13 separate spectral bands of data at varying spatial resolutions (ESA, 2019). The red, green, blue, and near infrared (NIR) bands are captured at the satellites' highest spatial resolution of 10 meters.

Healthy vegetation absorbs most red light while reflecting most NIR light. Normalized Difference Vegetation Index (NDVI) is a dimensionless metric calculated by examining the ratio of reflectance between red light and NIR light. This indicates whether or not the plant is healthy (NASA Earth Observatory, 2000). "False" NDVI using only the RGB bands can potentially be calculated as an estimate of plant health, though this method is not recommended when NIR data is available due to a higher potential for inaccuracy (Herrick, 2017). Multi-spectral satellite imagery has been successfully utilized to examine the health of control-targeted invasive plants at moderate resolutions (Agjee et al., 2015). This reduced or eliminated the need for traditional field assessments. Multispectral data at 10 m resolution from the Sentinel-2 satellite is sufficient to assess multiple acre patches of dense floating vegetation.

Several satellite imaging options are available for natural resource monitoring. Commercial satellites such as the Gaofen and Pleiades systems capture multispectral data at spatial resolutions of 2 meters or less, but are cost-prohibitive at $850 or more per image (ESA, 2019). Open source imagery is available from satellites such as GOES, MODIS, Landsat-8, and Sentinel-2. GOES and MODIS feature very high temporal resolution with daily return times and capture the necessary bands for NDVI calculation (NASA, 2018). However, they image at 1 kilometer and 250 meter spatial resolution, respectively. This resolution far too coarse for imaging the coves in this study. Landsat imagery could potentially be used, with a return rate of approximately two weeks and spatial resolution of 30 meters (Satellite Imaging Corporation, 2017). Sentinel 2, However, features a both superior return rate of approximately five days and higher spatial resolution of the red and NIR bands (10 meters) necessary for NDVI calculation (ESA, 2019). Sentinel-2 imagery represents the best compromise between spatial, spectral and temporal resolution of the available open-source satellite imagery resources, and was thus chosen as the satellite imagery source in this study.

Summary of Remote Sensing of Invasive Species

Satellite data from Landsat and Sentinel 2 can be accessed for free, which makes them invaluable tools for natural resource monitoring (Malasavi et al., 2019; Pastick et al. 2018). Software packages like ArcGIS and Agisoft PhotoScan aid in the monitoring process by mapping, quantifying, and evaluating invasive species. NDVI indices are reliable indicators of plant health and are thus useful to resource managers for evaluating the health of invasive plant species (Pastick et al., 2018 ; Wallace et al., 2016). Combined satellite/UAV imagery and subsequent analysis through GIS software have proven effective for invasive species management. The spatial extent of area selected can make high resolution satellite data cost-prohibitive in some studies; though low-cost, very high resolution data is possible to acquire for smaller areas via UAV. In some studies, UAV data has shown higher accuracy than satellite data and/or field survey (Bradley, 2014; Hill et al., 2017; Mullerova et al., 2017). The northern coves of Lake Carl Blackwell are ideal sites for a combined UAV/Satellite remote sensing study based on the homogenous stands of *N. peltata* vegetation, size of infested coves, and lack of obscuring canopy.

CHAPTER III

METHODS

This study combines elements of several recent studies including UAV image collection, subsequent orthophoto generation using Agisoft PhotoScan, and hand digitization to determine spatial coverage of *N. peltata*. Sentinel-2 satellite imagery from multiple dates was used to provide NDVI calculation for plant health assessment by performing raster calculations using the red and NIR reflectance bands.

The sites of this study comprise six northern coves (A through F) of Lake Carl Blackwell in north central Oklahoma (Figure 1). A pilot study was conducted on Cove D, which was then expanded to available data from all study coves. Cove D was imaged on five dates, Cove A on four dates, Coves B and F on three dates, and Coves C and E on two dates. All study coves excluding Cove B received glyphosate applications at least once between their UAV imagery dates.

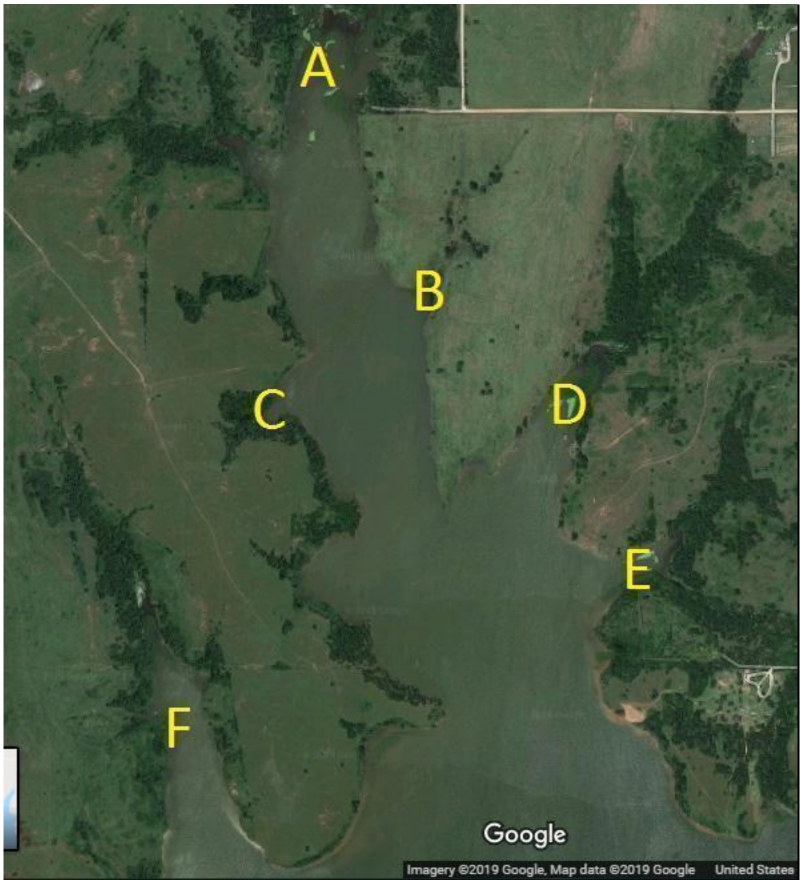
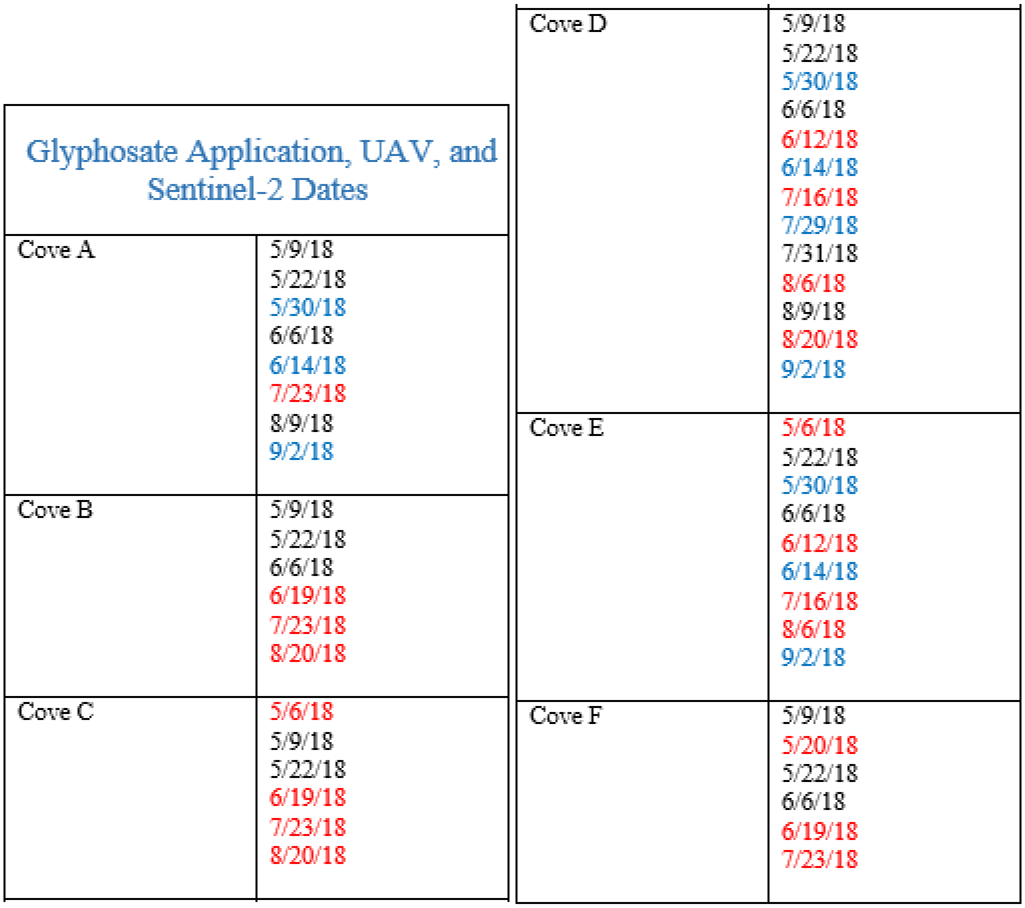


Figure 1: Site labels for the six study coves on Lake Carl Blackwell (image taken from Google Earth).

The glyphosate application schedule was not determined based on environmental conditions such as wind speed, temperature, etc. Glyphosate applications were scheduled approximately every two weeks through the growing season, but were subject to postponement due to high-traffic recreation times such as national holiday weekends.



Glyphosate Application, UAV, and Sentinel-2 Dates	
Cove A	5/9/18 5/22/18 5/30/18 6/6/18 6/14/18 7/23/18 8/9/18 9/2/18
Cove B	5/9/18 5/22/18 6/6/18 6/19/18 7/23/18 8/20/18
Cove C	5/6/18 5/9/18 5/22/18 6/19/18 7/23/18 8/20/18
Cove D	5/9/18 5/22/18 5/30/18 6/6/18 6/12/18 6/14/18 7/16/18 7/29/18 7/31/18 8/6/18 8/9/18 8/20/18 9/2/18
Cove E	5/6/18 5/22/18 5/30/18 6/6/18 6/12/18 6/14/18 7/16/18 8/6/18 9/2/18
Cove F	5/9/18 5/20/18 5/22/18 6/6/18 6/19/18 7/23/18

Table 1: Glyphosate application, UAV image capture dates, and Sentinel-2 capture dates for each cove on Lake Carl Blackwell spanning the entire period of this study. Glyphosate application dates are shown in red, UAV dates in black, and Sentinel-2 dates in blue.

A DJI Phantom 4 UAV was used to image Cove D at approximately 2 cm spatial resolution (flying height of approximately 50 m or 164 feet) on 5 dates (May 9th, May 22nd, June 6th, July 31st, and August 9th 2018). The UAV was outfitted with an off-the-shelf camera. It collected red (R), green (G), and blue (B) visible spectral bands. Each flight produced between 200 and 950 individual photos depending on the area of the cove. Orthomosaics were then generated from these images using Structure from Motion processing via Agisoft PhotoScan. GIS-based hand digitizing of *N. peltata* spatial extents were conducted in ArcMap 10.6 and consisted of outlining total *N. peltata* extent, identifying glyphosate-affected areas, and erasing open-water areas within the spatial extent.

Three feature classes were created for each date regarding *N. peltata*. These included total coverage, visibly stressed or non-healthy coverage (yellow and brown vegetation), and open water/other within the total coverage outline. The latter two feature classes were then used to clip the total coverage class to create a healthy *N. peltata* class. Imagery from different dates were then compared.

Hand digitization of UAV data was chosen over automated/semi-automated classification procedures such as pixel-based unsupervised classification or object-based image analysis. Figure 2 shows that small areas of Cove D were not included in image sets from every date, as can be noted in the northeastern tip of the cove. The full extent of missing cove area is covered with homogenous *N. peltata* vegetation, thus hand digitization can more accurately correct for this by relying on base maps and more complete orthophotos from other UAV image-capture dates. Neither pixel or object-based approaches offer a solution to correct and account for this missing area.

Three band (RGB) data may not be spectrally ideal for computer classification, leading to more noise and accuracy problems (Hill et al. 2017). . False NDVI was not calculated for these images, as it can produce less accurate results than true NDVI where the NIR reflectance band is available (Herrick 2017). Manual visual classification is more accurate than algorithm-based methods in some instances (Bradley 2014, Hill et al. 2017). Hand digitization was conducted on Cove D during the initial study, and subsequently applied to Coves A, B, C, E, and F.

To further validate the UAV data and analyses, NDVI was calculated using open source imagery from the Sentinel-2 satellite obtained via the Copernicus Open Access Hub (ESA, 2018). These images can be obtained after a free registration with Sentinel Scientific Data Hub. Once registered, the user can select an area of interest and time frame, then download from a list of available 290-kilometer-swath images. Red and NIR were used to create NDVI calculations in ArcMap 10.6 using the Raster Calculator tool. These images were then extracted using known *N. peltata* coverage polygons from dates closest to the satellite image capture (Figure 5). For simplicity, the pilot study on Cove D used NDVI health generalized thresholds as follows: 0-0.33 (Unhealthy); 0.33+ (Healthy) based on Taipale (2018). The pilot study utilized imagery from 2 dates - May 30th, 2018 and July 29th, 2018.

Expanding on this method, NDVI values were calculated on Coves A, D, and E at three different stressed-class thresholds of 0.33, 0.365, and 0.4. These values were chosen based on differences in NDVI thresholds between Taipale (2018), Adgee et al. (2015) and Martin et al. (2018). NDVI pixels above these thresholds were classified as moderately or very healthy, while values below these thresholds were classified as stressed/unhealthy. The Sentinel-2 image capture dates of May 30th, June 14th, and September 2nd of 2018 were chosen both for their lack of cloud cover and to coincide with UAV capture dates as closely as possible. The July 31st imagery was not utilized for Coves A and E, as there were no UAV data for comparative purposes. For consistency, further analysis of Cove D imagery from July 31st was not integrated into the expanded study. Only Coves A, D, and E have *N. peltata* spatial extents large enough for 10-meter resolution multispectral imagery from Sentinel-2 to be suitable for analysis.

Water quality on Lake Carl Blackwell was consistently monitored to ensure that glyphosate had not entered Oklahoma State's raw water supply. Samples were collected by boat at the water intake structure near the lake's dam via a Van Dorn Bottle at a depth of eight feet. These samples were collected every day for one week after spraying was conducted. During periods of inclement weather, samples were collected from the dam, at a point near the water intake structure. An additional weekly sample was taken at the point of entry for OSU's water treatment facility throughout the time frame of glyphosate applications (May-September). All samples were tested at Accurate Environmental and had results Below Practical Quantitation Limit (BPQL). The dilute glyphosate solution (.75%) did not enter OSU's raw water at detectable levels.

CHAPTER IV

FINDINGS

Cove D Pilot Study: Spatial Extent and NDVI

Figure 2 below illustrates the methodology for estimating *N. peltata* spatial extent and the resulting feature classes. Photo A is the orthophoto generated from UAV imagery collected by DJI Phantom 4 (July 31st shown). This was created using Agisoft PhotoScan. Photo B is the digitized outline of total *N. peltata* extent including rocks, open areas, or other types of vegetation. The teal areas in Photo C represent visibly stressed *N. peltata* extent (yellow, brown, or black in color). The additional purple areas of Photo D are open water, rocks, and vegetation other than *N. peltata*. The feature class in Photo E represents healthy *N. peltata* extent. It is the result of clipping total extent (A) with the stressed *N. peltata* and open water/other feature classes.

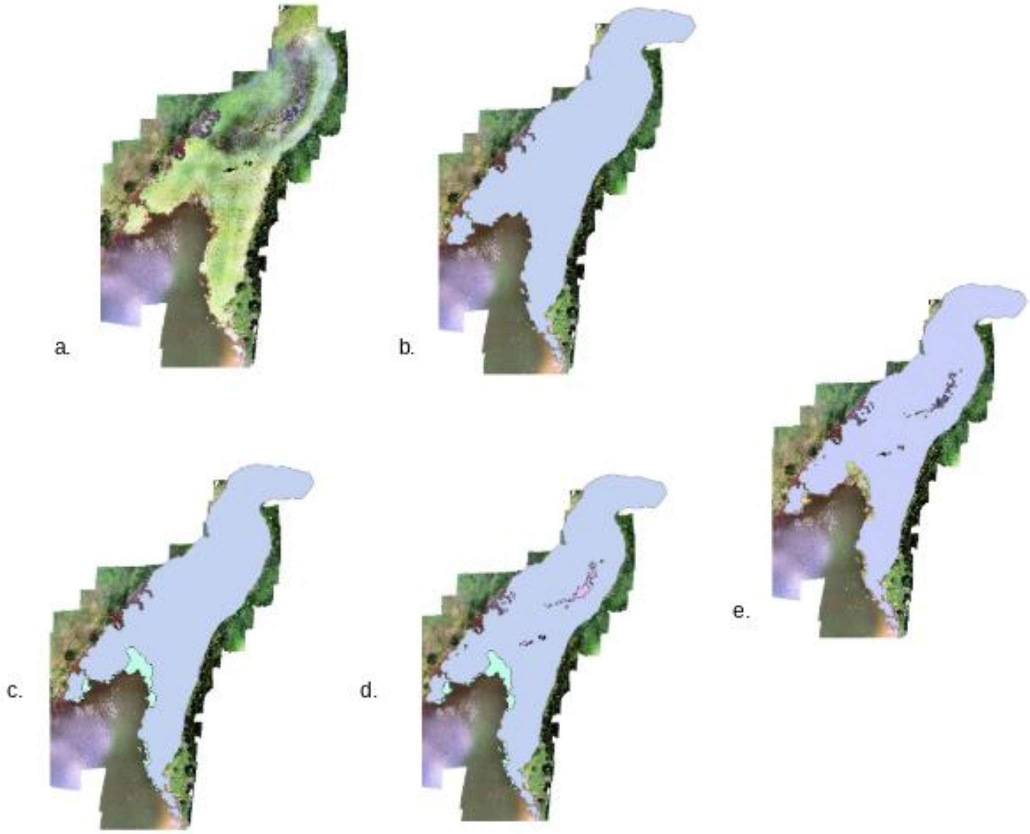


Figure 2: Five-step digitization process for determining healthy *N. peltata* extent, from orthophoto (a.) to healthy yellow floating heart coverage (e.).

Total *N. peltata* on Cove D expanded over the study period, as can be observed visually in Figures 3 and 4. Glyphosate had little effect on vegetation on Cove D as well, with the highest visually stressed *N. peltata* at 5.29% before the first spraying event of 2018. This may be a lingering effect from September 2017 glyphosate application.

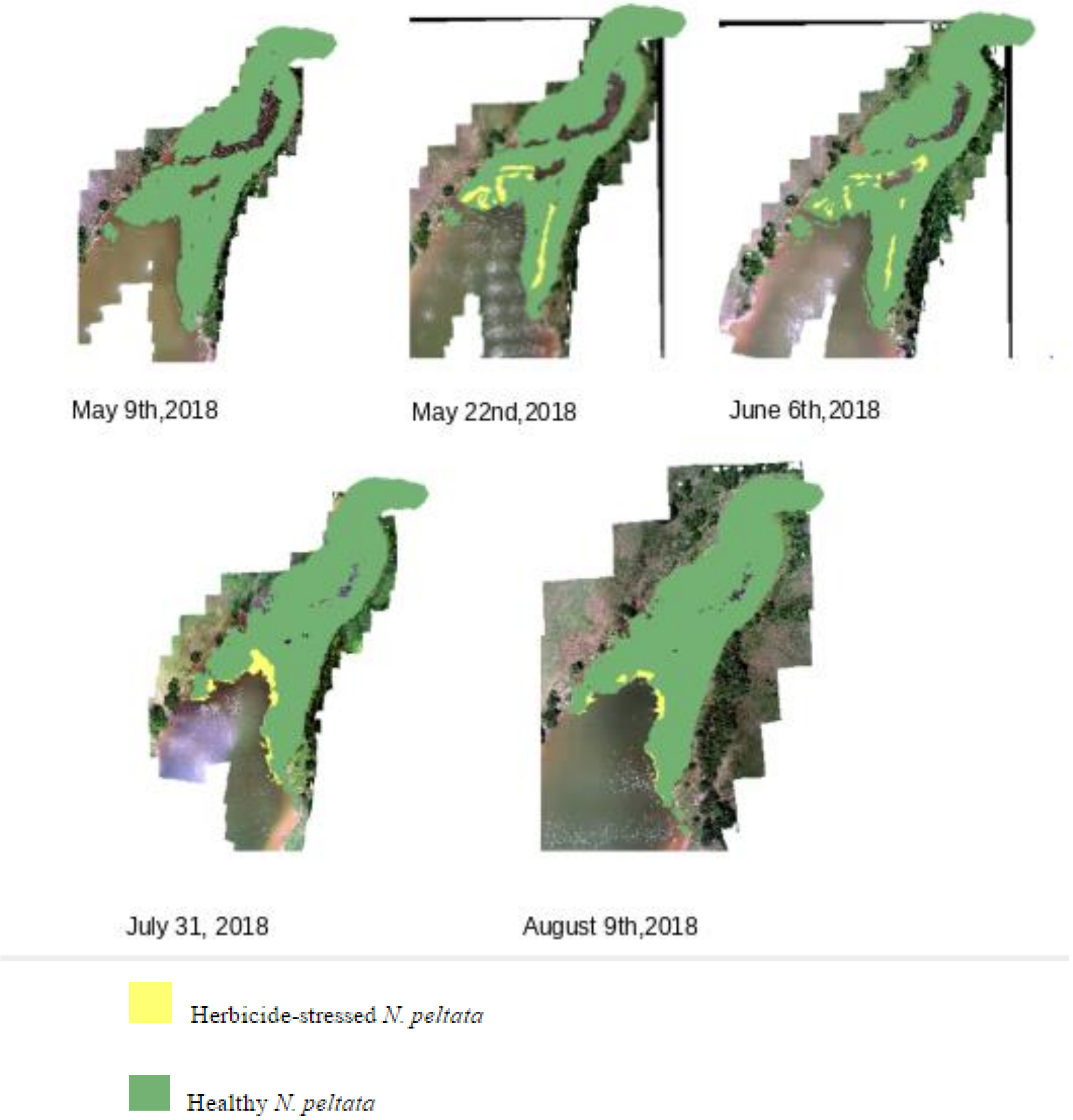


Figure 3: Digitized polygons of healthy vs. stressed *N. peltata* extent for each monitoring date on Cove D. Yellow represents stressed *N. peltata*, green represent healthy *N. peltata* coverage. Glyphosate applications on Cove D were conducted on three dates during this time period: June 12th, July 16th, and August 6th.

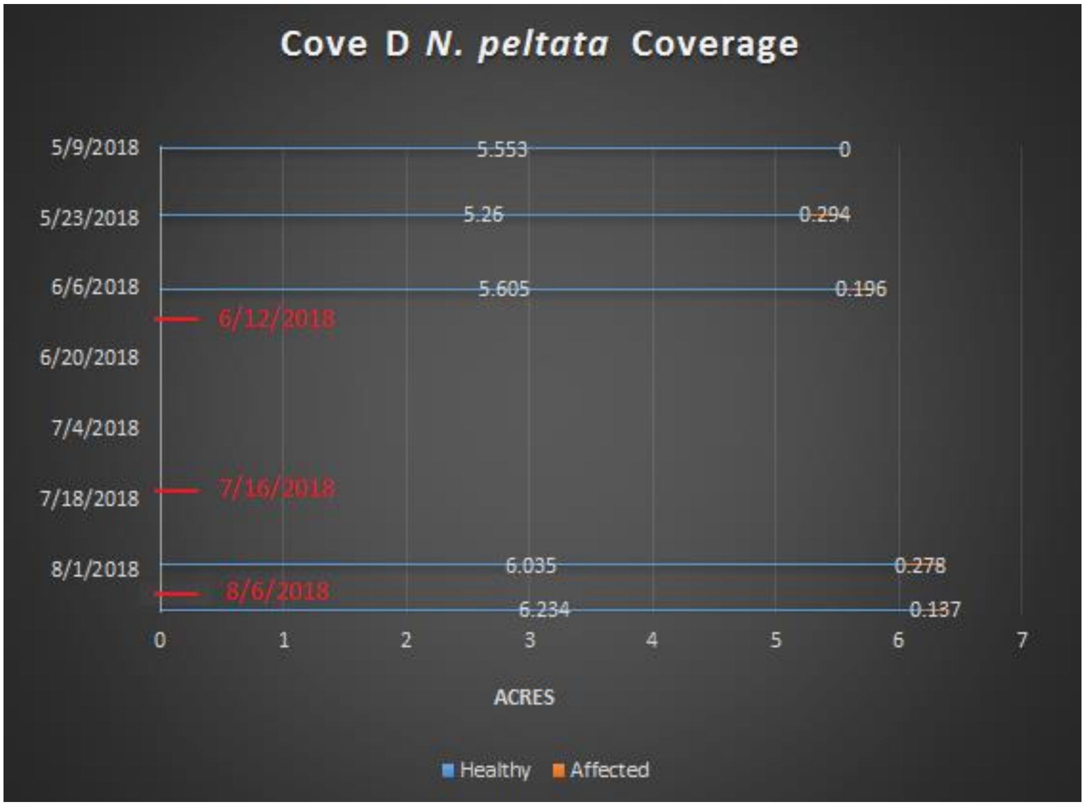


Figure 4: Bar graph of glyphosate-affected *N. peltata* vs healthy *N. peltata* extent on Cove D. Glyphosate application dates are marked in red.

Multispectral imagery from Sentinel-2 was used to calculate NDVI results. These results were extracted via digitized extent coverage polygons for May 30th and July 29th on Cove D as part of the pilot study.

The digitized polygon from May 22nd (Figure 5) was used to extract Sentinel 2 satellite NDVI data from May 30th. Pixels at 100m² spatial resolution had values from 0.27 (stressed) to 0.78 (healthy). The full spatial extent of Cove D had a mean NDVI of 0.59, which indicates vegetation, was on the high side of the moderately healthy range for this date. Only two pixels (200m²) of vegetation fell into the unhealthy or stressed vegetation class (<0.33). This indicates that approximately 0.89% of total *N. peltata* coverage was stressed on this date.

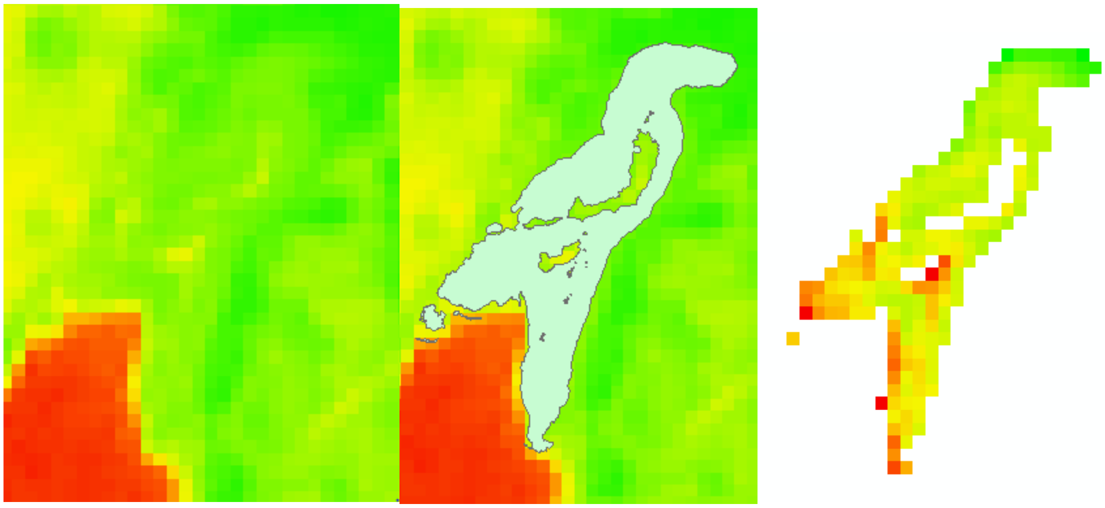


Figure 5: Polygon of *N. peltata* coverage from May 22nd used to extract May 30th NDVI raster. This way individual *N. peltata* coverages can be isolated.

This process was repeated using Sentinel data from July 29th and a UAV-generated coverage polygon from July 31st, after two herbicide applications had taken place (Figure 6). Values ranged from .11 to .77 with an average of .58 for over the extent of Cove D. Four pixels (400m^2) of coverage fell below the 0.33 NDVI threshold for unhealthy vegetation. This indicates an *N. peltata* stress rate of 1.57%. The percentage increased from the May 30th data, but still below any reasonable goals for control of the species in Cove D.

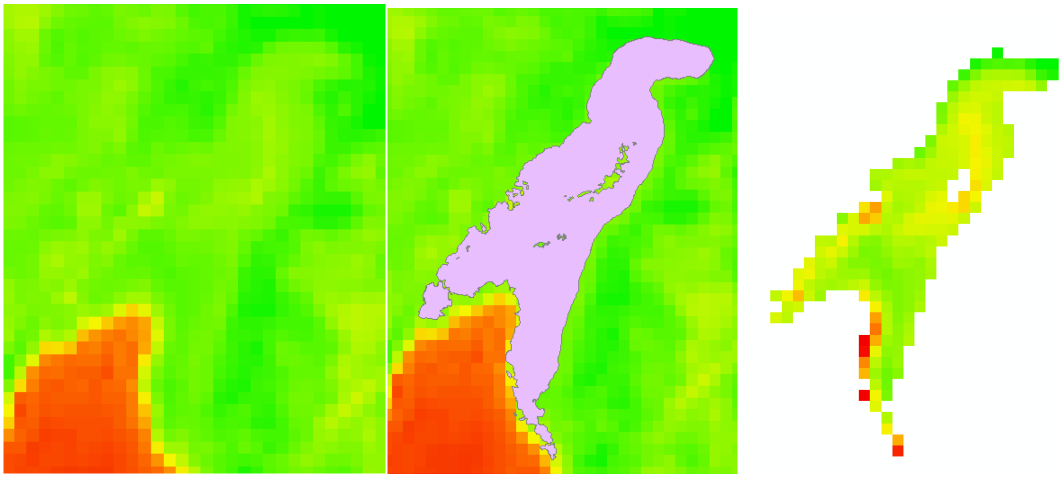


Figure 6- Polygon of *N. peltata* coverage from July 31st used to extract July 29th NDVI raster.

Expanded Study: Spatial Extent and NDVI

Cove A had the largest *N. peltata* spatial extent of any single cove and was thus the most significant component to the expanded study. Glyphosate was applied to Cove A on July 23rd, 2018, between the third and fourth UAV dates. Imagery from August 9th showed the first RGB-visible stress signs. Figure 7 shows that the overall spatial extent of Cove A expanded 9.08% from 14.307 acres to 18.173 acres, with 1.651 acres of herbicide-affected coverage. The relatively expansive coverage of *N. peltata i*n Cove A precluded the glyphosate from affecting further than the first 20 linear meters of spatial extent. The glyphosate sprayer used lacked the necessary pressure to apply a sufficient quantity of glyphosate and surfactant to the entire *N. peltata* spatial extent in these coves. *N. peltata* control via glyphosate application was unsuccessful.

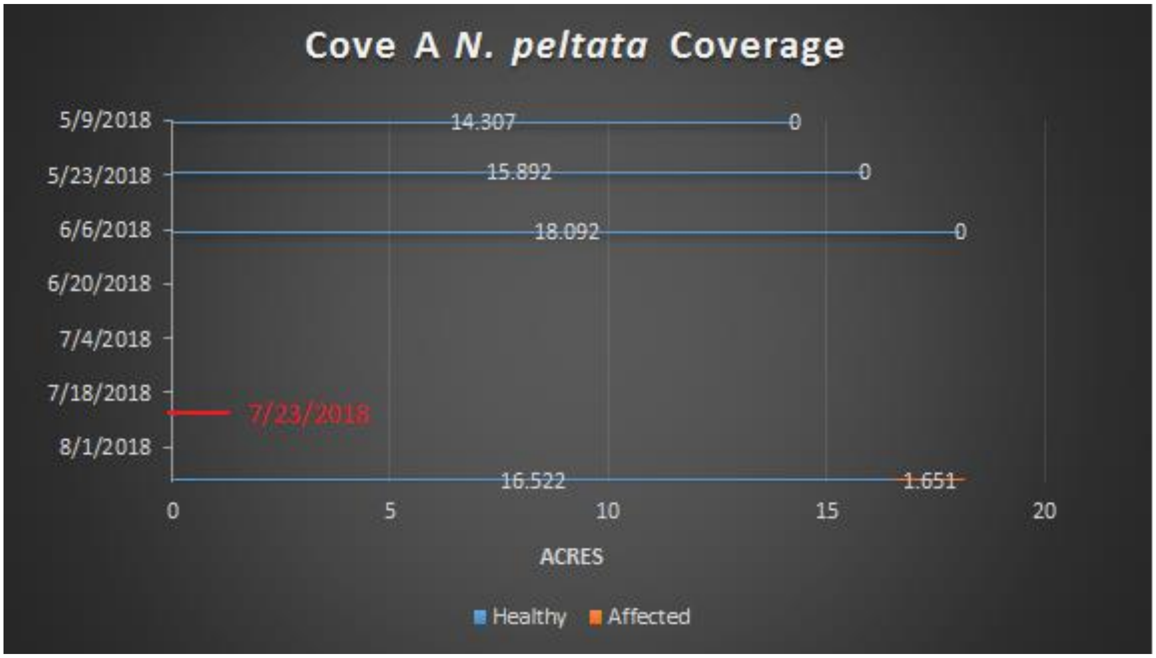


Figure 7: Changes in spatial extent of healthy and healthy/affected vegetation for Cove A. Glyphosate application date marked in red.

Figure 8 shows the methodology applied to extract Sentinel-2 NDVI using UAV generated polygons of *N. peltata* spatial extent. Only Coves A, D, and E had homogenous *N. peltata* spatial extents suitable for this analysis. The resulting NDVI rasters were then analyzed by cove.

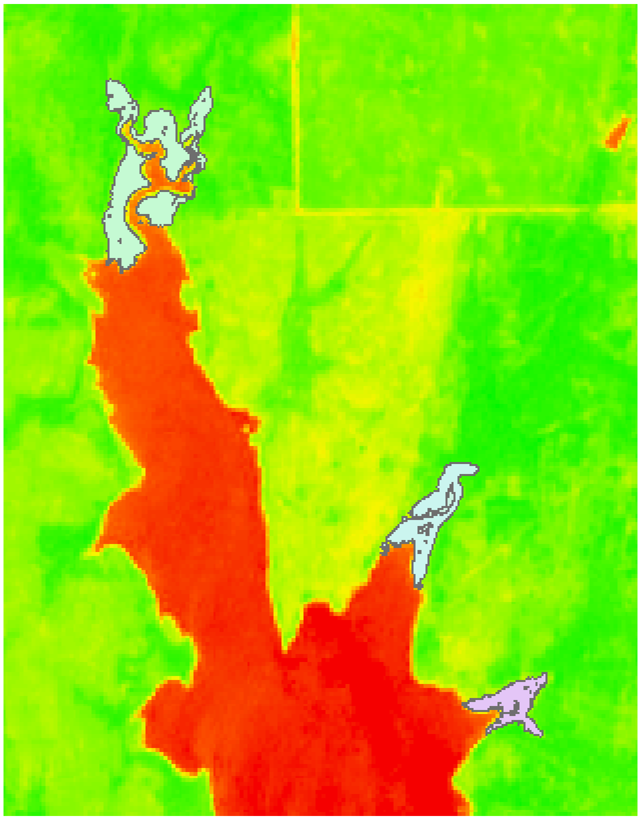


Figure 8: *N. peltata* spatial extent polygons from May 22nd, 2018 UAV flight used to extract NDVI from May 30th, 2018.

Mean NDVI of *N. peltata* coverage for Cove A (Figure 9) decreased from 0.581 to 0.549 (5.51%) from May 30th to September 2nd. This decrease in mean showed insufficient stress of *N. peltata* treatment between these dates, as 0.549 is still well within the moderately to very healthy range of >0.33 NDVI.

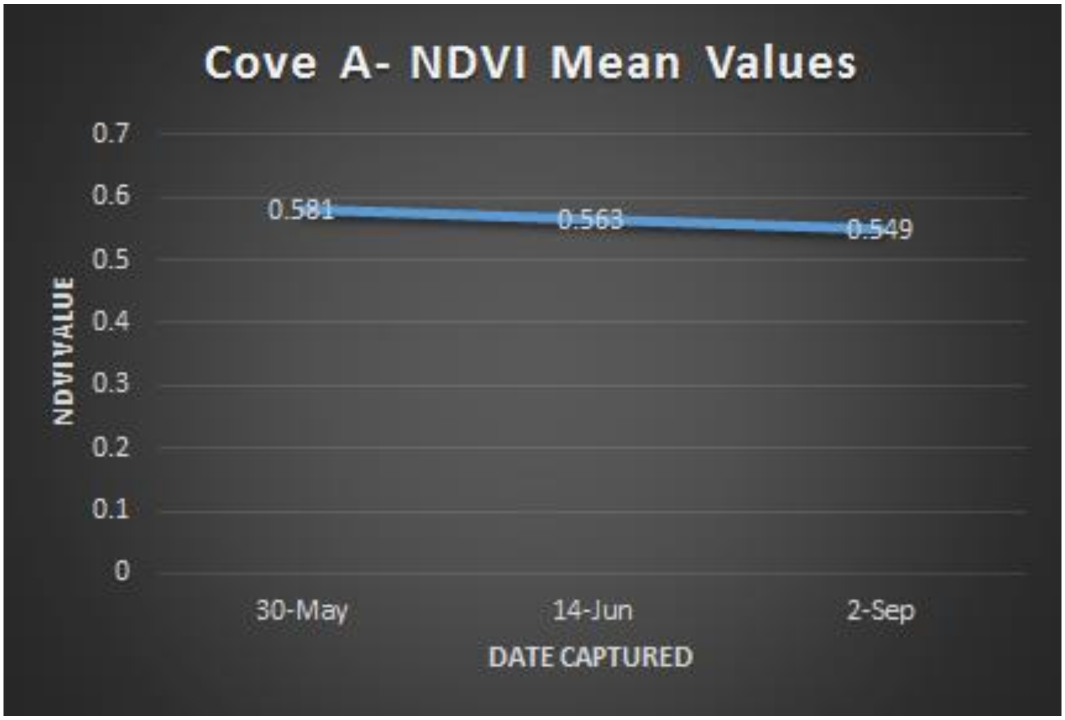


Figure 9: Mean NDVI values for Cove A.

Cove B had glyphosate applied for the first time in 2018 on June 19th. The three UAV image captures for Cove B occurred before glyphosate application. Cove B can thus be observed as an example of *N. peltata* expansion in a small (<1 acre) cove from early to midway through the growing season without herbicide interference. Spatial extent of *N. peltata* in Cove B increased 4.95% between May 9th and May 22nd and 6.33% between May 22nd and June 6th (Figure 10). Cove B expanded from 0.707 acres to 0.789 acres of *N. peltata* spatial extent, with no visible effects of a previous 2017 treatment.

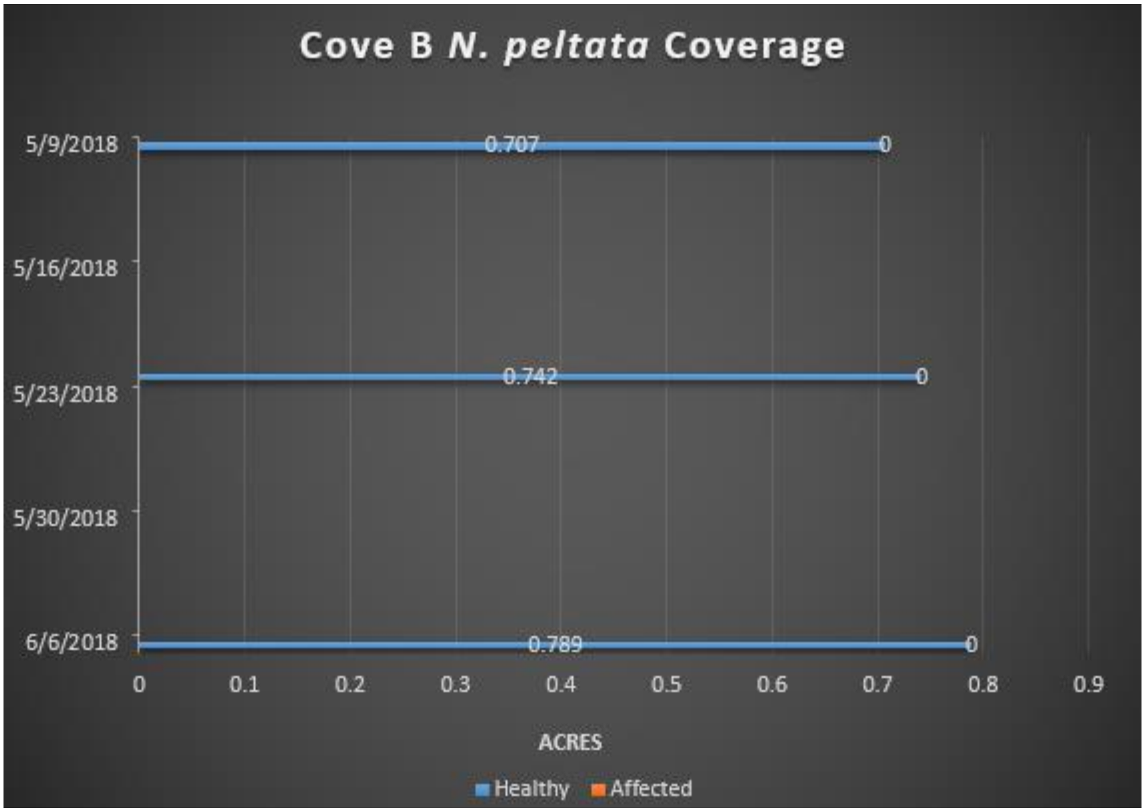


Figure 10: Changes in spatial extent of healthy and stressed/affected vegetation on Cove B.

Glyphosate was effective at reducing total *N. peltata* spatial extent in Cove C (Figure 11) from 0.185 acres to 0.163 acres. Glyphosate yielded a reduction of over 20% in Cove C, while visibly affecting an additional 23.4% of the remaining coverage.

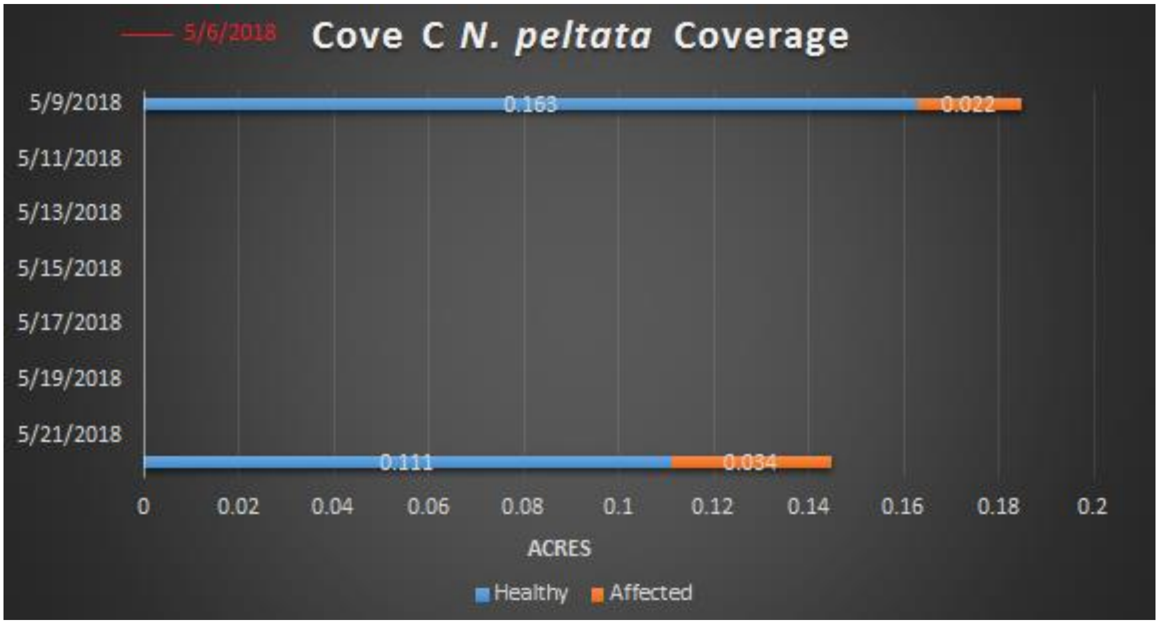


Figure 11: Changes in spatial extent of healthy and stressed/affected vegetation for Cove C. Glyphosate application date marked in red.

Orthophoto digitization estimated a reduction in Cove E from 3.465 acres to 3.447 acres of total coverage, with 16.1% of the remaining spatial extent affected by glyphosate. Cove E is the only cove large enough for effective Sentinel-2 imaging that decreased in total *N. peltata* extent, though this decrease was a modest 0.52% between May and June UAV dates.

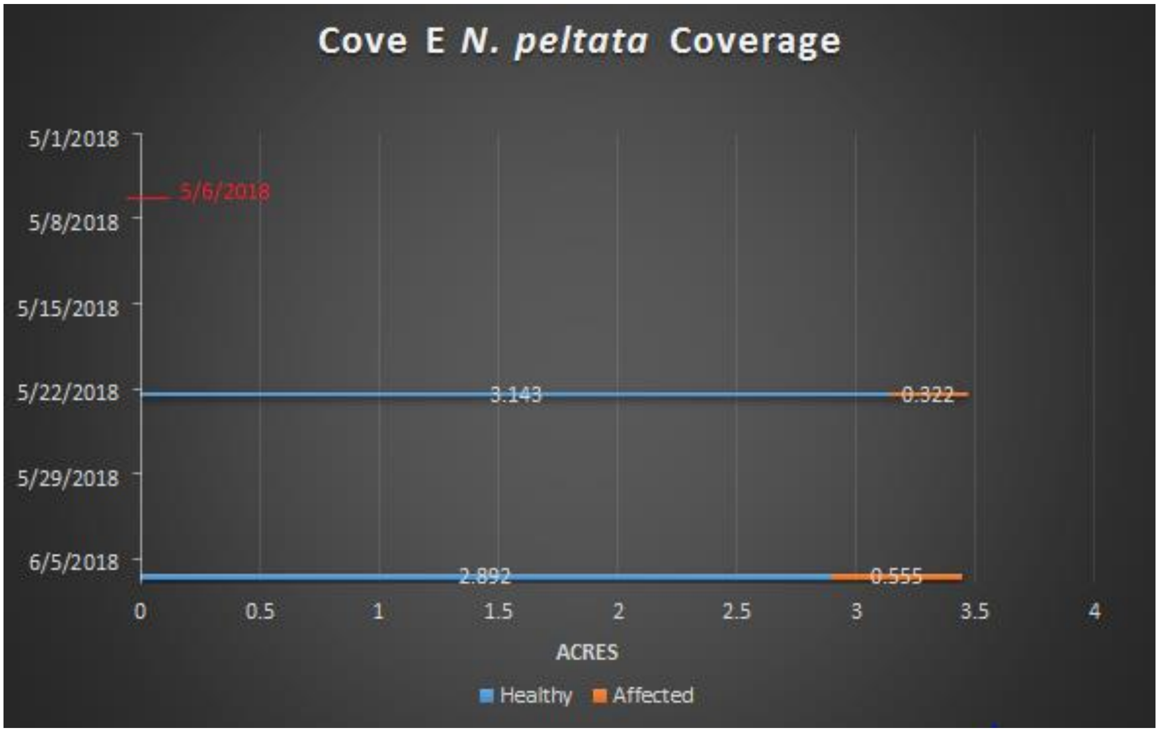


Figure 12: Changes in spatial extent of healthy and stressed/affected vegetation for Cove E. Glyphosate application date marked in red.

Mean NDVI value increased 11.5% from 0.546 and 0.617 between May 30th and September 2nd for Cove E (Figure 13). The polygon created from June 6th UAV imagery was used to extract the September 2nd NDVI data, as this was the last UAV date flown. This is suitable for mean calculation, but eliminated Cove E from comparison with UAV-digitized stress areas.

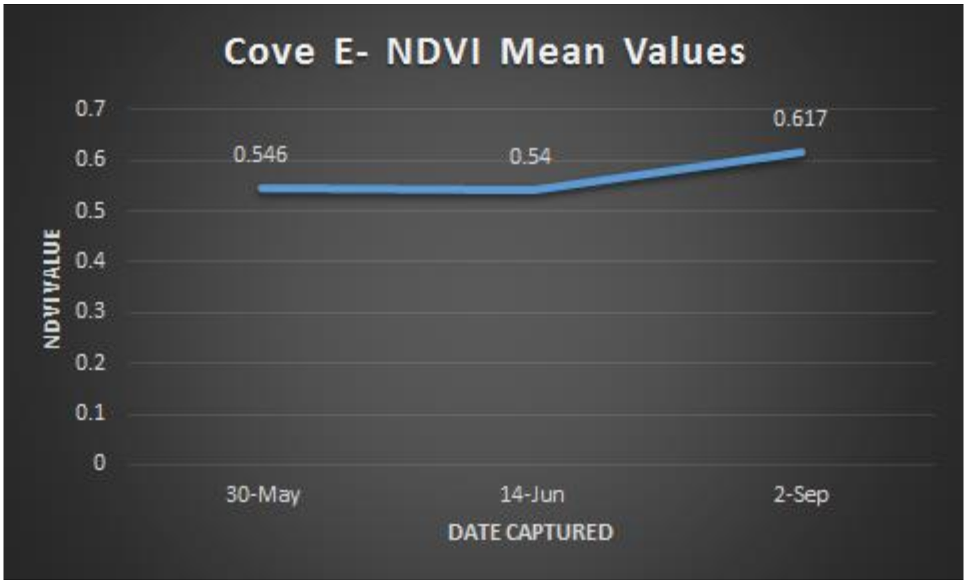


Figure 13: Mean NDVI values for Cove E.

Cove F increased in spatial extent from 0.84 acres to 1.62 acres before glyphosate application (Figure 14). Its coverage reduced to 1.235 acres after application. Herbicide-stressed vegetation was estimated at 63.72% of this remaining spatial extent, as 0.448 acres appeared photosynthetically healthy. This was the highest stress rate of any cove.

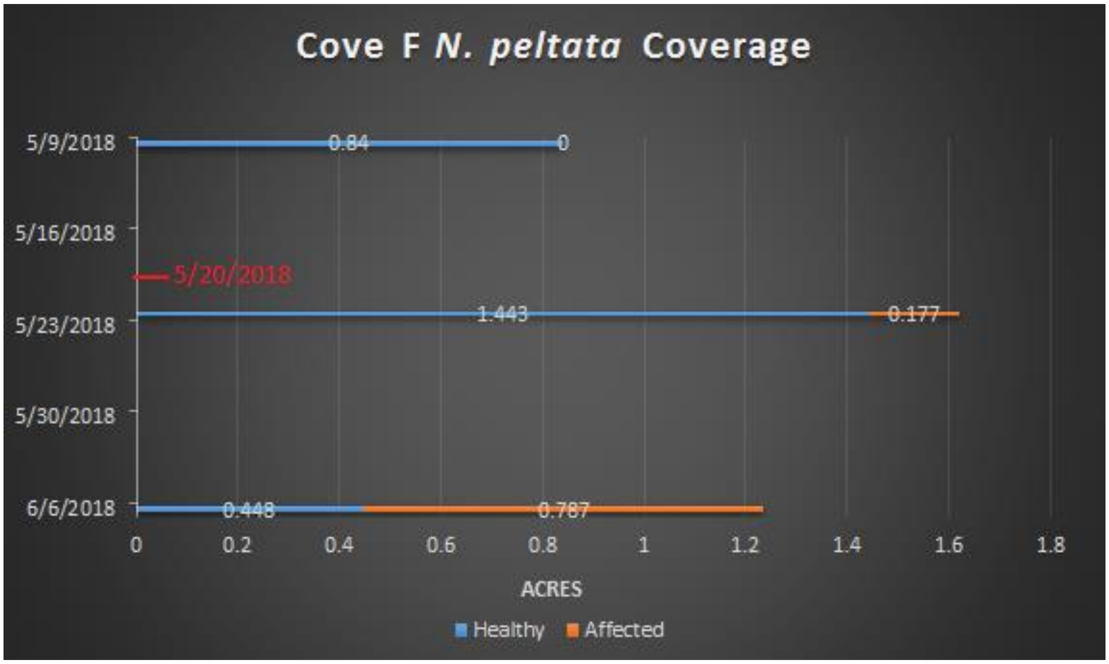


Figure 14: Changes in spatial extent of healthy and stressed/affected vegetation for Cove F. Glyphosate application date marked in red.

UAV vs. Different NDVI Thresholds

Cove A did not have UAV-visible signs of stress in May and June, though Sentinel-2 remotely sensed small percentages of low NDVI before glyphosate application (Figure 15). The 0.33 Sentinel threshold for August/September was the closest in percentage to the UAV-estimated value.

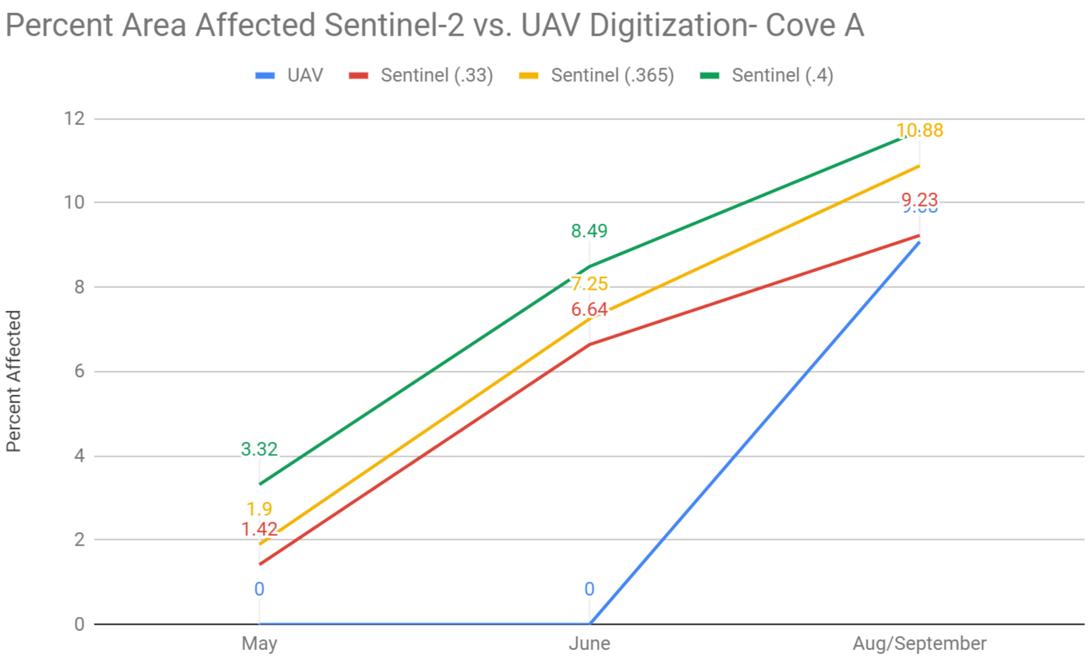


Figure 15: Comparison of stress estimated by Sentinel-2 imagery and UAV digitization for Cove A.

Figure 16 indicates that stress estimations digitized from UAV imagery did not align with NDVI values on Cove D for May and August/September. Though June values were not significantly different from each other, a clear inverse trend exists between NDVI calculated values and hand digitization across these three image sets. This could have occurred due to the wide spatial resolution gap between UAV and Sentinel-2 imagery, and/or could be indicative of plant stress invisible through the RGB bands but detectable through multispectral analysis. The 0.33 threshold was the closest in percentage-stressed value to the UAV estimation.

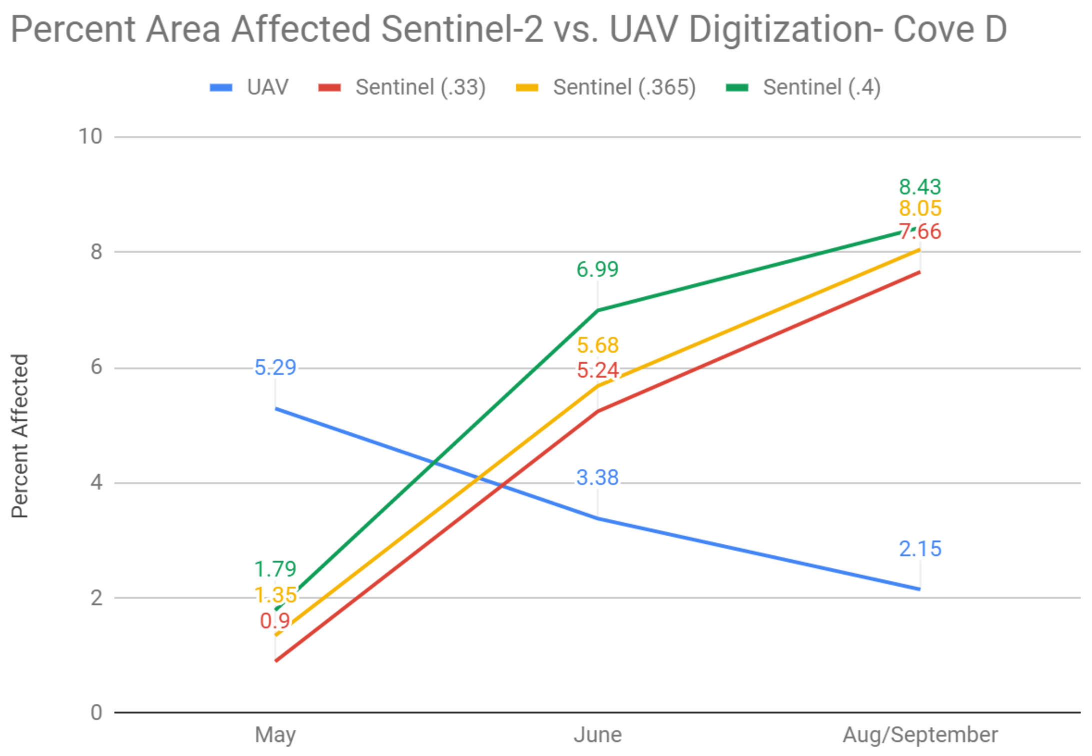


Figure 16: Comparison of stress estimated by Sentinel-2 imagery and UAV digitization on Cove D. NDVI stress calculations increased over time, while visible stress estimates decreased.

Cove E was UAV-imaged for the final time on June 6th, 2018; no UAV digitized stress polygons were available to compare against September 2nd NDVI values. For this reason, a bar graph was used to represent the findings for Cove E. Figure 17 shows that UAV digitization overestimated stress in May and June as compared to NDVI calculation. The 0.4 threshold was closest to UAV percentage values for both months.

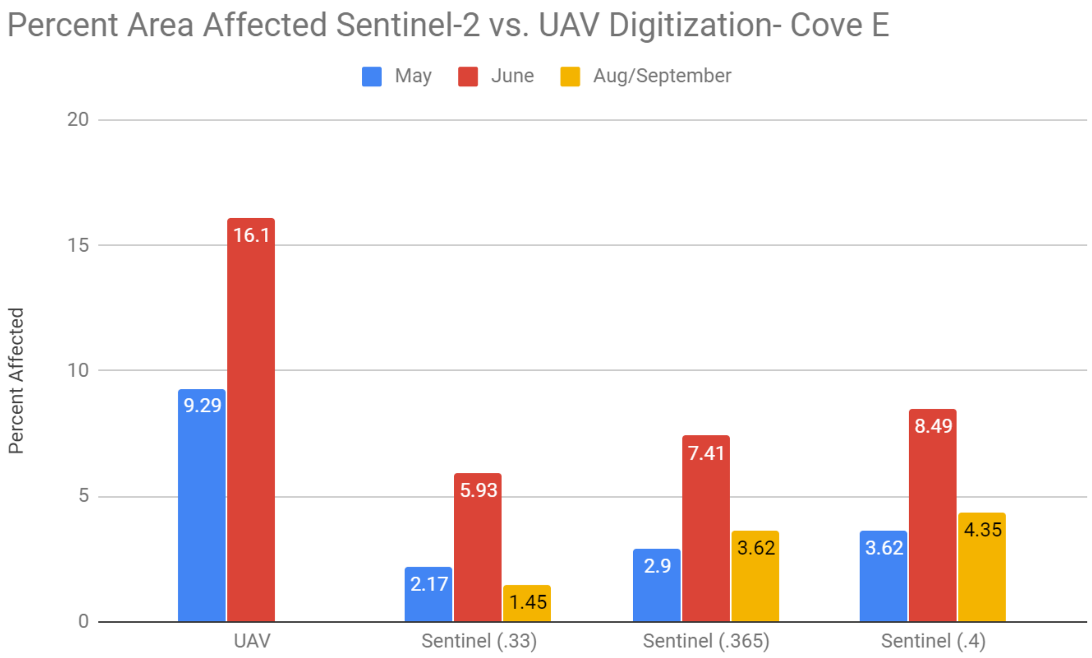


Figure 17: Comparison of stress estimated by Sentinel-2 imagery and UAV digitization on Cove E.

Wind and Waves

Wind may have been a significant factor in the disparity between the glyphosate-applied coves that expanded total coverage (A, D) and reduced total coverage (C, E, and F). Prevailing south winds in Oklahoma are a common occurrence during these months. The wind, combined with the long fetch of Lake Carl Blackwell from south to north, consistently produced large waves on the north end of the lake. Coves C and D are sheltered from north/south waves due to their shape and positioning (Figure 1). Cove F itself is not similarly positioned, though the *N. peltata* patches within the cove were sheltered from wind/wave action either by coastline (Figure 18) or by native stands of vegetation (Figure 19).

Figure 18: *N. peltata* patch on Cove F on May 22 (left) and June 14 (right). Note the natural southern wind/wave break from the coastline.

Figure 19: Northernmost *N. peltata* patch Cove F on May 22nd (left) and June 14th (right). Note the native vegetation stands circled in red and the retraction/ stress of *N. peltata* over time.

Wind/wave breaks likely protected these coves from wash-off from waves. This likely increased glyphosate contact time and glyphosate efficacy. *N. peltata* patches in

Coves A and D face directly or near directly to the south, and were thus subjected to glyphosate wash-off.

The size of *N. peltata* extent patches may have also played a significant role in glyphosate efficacy. As noted by the applicator, smaller patches were more easily accessible both by boat and from land. This led to more complete glyphosate coverage (Koenig 2018). Combined with the required contact time for glyphosate efficacy, this likely led to better results in smaller *N. peltata* patches rather than larger ones.

Issues with Data Collection

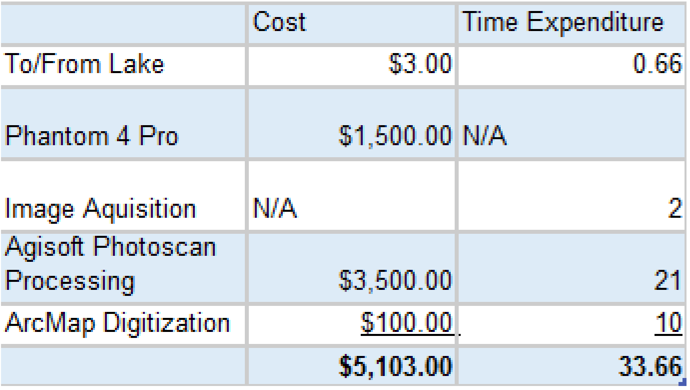
Oklahoma City, Oklahoma (approximately 50 miles southwest of the study site) has an average of 12 days per month from May-September with 30% or less cloud coverage (Current Results Publishing Ltd., 2019). Cloud coverage conditions on Lake Carl Blackwell can be assumed as reasonably close to this average. This substantial amount of cloud cover presents a challenge for remote sensing via satellite, as clouds often render satellite imagery unusable during this time. UAV image acquisition is not cloud-limited in the same way, as the UAV flies low enough to avoid them. Total cloud coverage is often the ideal condition for UAV flights, as it can eliminate sun glare. Wind plays a factor for UAV image acquisition; DJI recommends that the Phantom 4 Pro should not fly in wind speeds of 22 miles per hour or more (2019). UAVs have greater timing flexibility with data collection as compared to Sentinel-2, as UAV flights can be scheduled and conducted during favorable climatic conditions such as minimal cloud coverage and minimal wind velocity. Climatic conditions presented a challenge for both glyphosate efficacy and remote sensing via UAV and Sentinel-2 during this study.

The flying height and resulting spatial resolution of DJI Phantom 4 Pro was chosen consistent with Hill et al. (2017) at just over 2 cm. This very fine resolution data was able to capture multiple pixels for each small flower, which would likely have improved computer classification accuracy. Since computer-based classification was not selected as a viable method for these particular image sets, the added time resources used to image and process the coves at this resolution may have outweighed the benefits of higher-resolution images. Since the *N. peltata* coverage was estimated via manual digitization, increasing the flying height spatial resolution of images could aid in collecting more complete image sets of the coves without compromising the accuracy of spatial extent estimations. Doubling the spatial extent to ~5 cm would produce orthophotos suitable for manual classification of *N. peltata* in much less time.

Costs Associated with *N. peltata* Monitoring and Management

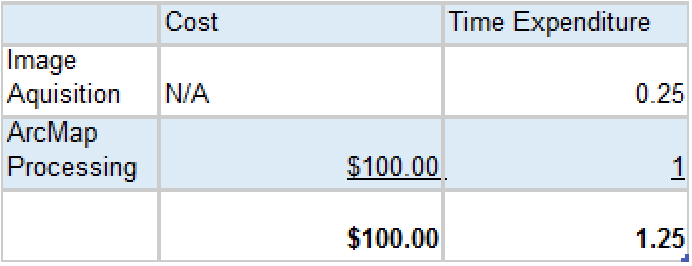
For larger coves such as A, E, and D, 10 m spatial resolution for spectral assessment is sufficient to gauge the health of *N. peltata* throughout the growing season. Utilizing Sentinel-2 imagery for *N. peltata* monitoring requires substantially less monetary and time resources than UAV monitoring. Sentinel-2 imagery is freely available through the online Copernicus Open Access Hub courtesy of the European Space Agency, thus data acquisition and subsequent processing in ArcMap total just over an hour of time. UAV monitoring requires additional hardware and software for data collection and processing. The DJI Phantom 4 Pro and Agisoft Photoscan Professional license require a combined initial cost of approximately $5000. Time for UAV flight, PhotoScan processing, and digitization combine to over 30 hours for a set of six coves.

Higher spatial resolution is a more significant factor when deciding which remote sensing tool to use for small (1 acre or less) coves. The relatively high cost of UAV monitoring (Table 2) to Sentinel-2 monitoring (Table 3) is a necessary expenditure for Coves B, C, and F. The spread and/or reduction of *N. peltata* in these coves cannot be effectively monitored by Sentinel-2 10 m resolution sensors, as the spatial extent of their *N. peltata* patches is often less than 100 m^2. The UAV imagery in this study played a critical role in identifying and quantifying small patches of stressed vegetation, as was the case in Cove F. Sentinel-2 effectively supplemented UAV data from a spectral perspective, but could not replace the much finer resolution for estimated *N. peltata* spatial extent.



	Cost	Time Expenditure
To/From Lake	$3.00	0.66
Phantom 4 Pro	$1,500.00	N/A
Image Aquisition	N/A	2
Agisoft Photoscan Processing	$3,500.00	21
ArcMap Digitization	$100.00	10
	$5,103.00	**33.66**

Table 2: Cost and time (hours) for one UAV image analysis date (6 coves).



	Cost	Time Expenditure
Image Aquisition	N/A	0.25
ArcMap Processing	$100.00	1
	$100.00	**1.25**

Table 3: Cost and time (hours) for one Sentinel-2 NDVI calculation (3 coves)

Due to proactive and successful *N. peltata* management on Lake Carl Blackwell's southern coves in 2017, revenue from campsite purchases and daily permit sales have not been affected thus far. However, significant opportunity costs are associated with glyphosate application and monitoring of *N. peltata*. Lake Carl Blackwell spent approximately $67,000 on *N. peltata* management in 2018 including glyphosate application, sampling, and graduate student employment. This cost has postponed plans to build two new pavilions (~ $30,000 each) on the southern end of the lake. Future lake improvement plans include bunkhouses (~$65,000 each) and a new conference room facility (~$300,000+). According to Lake Carl Blackwell manager Brian Brinker, the resource expenditures needed to manage *N. peltata* over the past two years have delayed and will continue to delay these projects until *N. peltata* is eradicated on Lake Carl Blackwell.

Next Steps for *N. peltata* Management

Limitations of this study include the wide gap between Sentinel-2 and UAV spatial resolution. Only N. peltata patches on coves A, D, and E could be effectively evaluated using the relatively course Sentinel-2 imagery, and stressed-coverage NDVI calculations did not statistically align with UAV data on coves D and E. More UAV data on all coves would be ideal to supplement data from Sentinel-2 and more effectively track the spread and/or reduction via digitization.

Sentinel-2 imagery should continue to be utilized to supplement UAV imagery for Coves A, D, and E. The spectral information provided by Sentinel-2 sensors can continue to provide health assessments of *N. peltata* in these larger coves. Fine-resolution UAV imagery should also continue in these coves to monitor spatial extent before and after

ProcellaCOR application.UAV flights should prioritize Coves B, C, and F moving forward, as Sentinel-2 spatial resolution is to coarse for analyzing these coves.

As glyphosate has not been proven to be an effective aquatic herbicide for Yellow floating heart in this case, another approach has been decided upon. ProcellaCOR by SePRO is a genus-specific herbicide applied below the water surface for root system uptake. This herbicide has been recently tested on *N. peltata* on a small pond (<1 acre) by the Wisconsin Department of Natural Resources at a 100% efficacy rate. ProcellaCOR is considered to be of very low toxicity to humans and other mammals, fish, birds, bees, reptiles and amphibians (Wisconsin Department of Natural Resources, 2018). ProcellaCOR will be applied in July of 2019 in place of glyphosate on Lake Carl Blackwell. Future studies will continue the use of both satellite imagery and UAV data acquisition to track *N. peltata* health.

CHAPTER V

CONCLUSION

Glyphosate did not stress or kill *N. peltata* effectively overall in the northern coves of Lake Carl Blackwell over the 2018 growing season. On Cove D, NDVI calculations showed less than 1% of *N. peltata* coverage as stressed in the early season (May 22nd) before the first application and just over 1% during peak season (July 29th) after two spraying events.

Estimations for stressed *N. peltata* extent on Cove D were lower for the NDVI calculations as compared to hand digitization. This could suggest that most areas of yellow/ brown *N. peltata* visible from UAV imagery remained photosynthetic. However, the stress effects of glyphosate were localized when pixels are viewed relative to each other, as both May and July imagery had approximately the same mean NDVI values (0.59 and 0.58, respectively). This could suggest an accumulative effect of glyphosate over time in small areas of *N. peltata* coverage.

The *N. peltata* infestation on Cove A is the largest, most significant area of *N. peltata* coverage on Lake Carl Blackwell. The spatial extent of *N. peltata* on Cove A continued to expand throughout the 2018 growing season, despite approximately 9% affected vegetation visible after glyphosate application. Analysis from digitization and Sentinel-2 imagery showed the stressed vegetation along the perimeter of the *N. peltata* extent accessible by boat (Appendix D). The magnitude of *N. peltata i*n Cove A precluded the spraying apparatus from affecting further than the first 20 linear meters of spatial extent, making effective *N. peltata* control via glyphosate application unsuccessful.

Cove B was not treated with herbicide before the three dates of imaging, and expanded consistently during the timeframe of this study. Spatial extent of *N. peltata* in Cove B increased by 4.95% between May 9th and May 22nd. This spatial extent increased by 6.33% between May 22nd and June 6th. Cove B could serve as a control for a typical small cove left untreated between early May and early June.

Glyphosate application of Cove C was more effective relative to every other cove excluding Cove F, with a total extent reduction of over 20%. This could be explained in part by the relatively small spatial *N. peltata* spatial extent combined with natural windbreak of coastline from south-north winds increasing glyphosate contact time.

Cove E was the only large *N. peltata* infestation (over two acres) that had total *N. peltata* spatial extent reduced over the UAV study period. Visibly stressed areas were detected on May 22nd, 2018 and expanded on June 6th, along with a small (>10%) reduction in total coverage.

Glyphosate application was more effective on Cove F than in any other study cove by a substantial margin. Cove F had the largest total reduction of *N. peltata* spatial extent along with stressed vegetation extending over 60% of the remaining coverage. Total coverage increased from 0.84 to 1.62 between May 9th and May 22nd, then decreased 23.77% from May 22nd to June 6th.

Results of comparisons were inconclusive as to which NDVI threshold is most similar to UAV digitization of stressed vegetation between 0.33 and 0.4. The stressed area percentage created from the 0.33 threshold was closest to the UAV estimations for Coves A and D. On Cove E, the 0.4 threshold was most similar to the UAV value.

Glyphosate did not achieve desired *N. peltata* mortality rates, with particularly low efficacy in large infestations without windbreaks provided by coastline and/or stands of native vegetation. The 2018 glyphosate applications on five of the six study coves did not match the retraction rates of glyphosate applications in 2017 on Lake Carl Blackwell's southern coves (Koenig 2017). The 2018 applications were likely affected by the long fetch and consequent wave action in the northern coves of Lake Carl Blackwell. These results are contrary to the mesocosm glyphosate studies on macrophytes by Fairchild et al. (2002) and Cruz et al. (2015), in which glyphosate achieved mortality at much higher rates.

Sentinel-2 imagery should continue to be used to supplement UAV imagery for Coves A, D, and E from this study. Sentinel-2 sensors can provide spectral indices like NDVI to monitor *N. peltata* health. UAV imaging should continue in these coves to monitor spatial extent on a finer scale before and after ProcellaCOR application in July of 2019. Monitoring using UAV imagery should prioritize the smaller cove infestations of

B, C, and F moving forward for spatial extent estimations of smaller *N. peltata* patches. Coves A, D, and E could continue to be spectrally evaluated using NDVI extracted from UAV-generated coverage polygons using the methods described in this study.

Due to the low efficacy rates of glyphosate application, ProcellaCOR will be applied in July 2019. Studies on the efficacy of ProcellaCOR will continue on Lake Carl Blackwell via remote sensing. Water quality will continue to be a priority and will be tested for by Oklahoma State University. Samples will be split between a SePro laboratory and the laboratory at the Oklahoma Department of Environmental Quality.

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APPENDICES

Appendix A

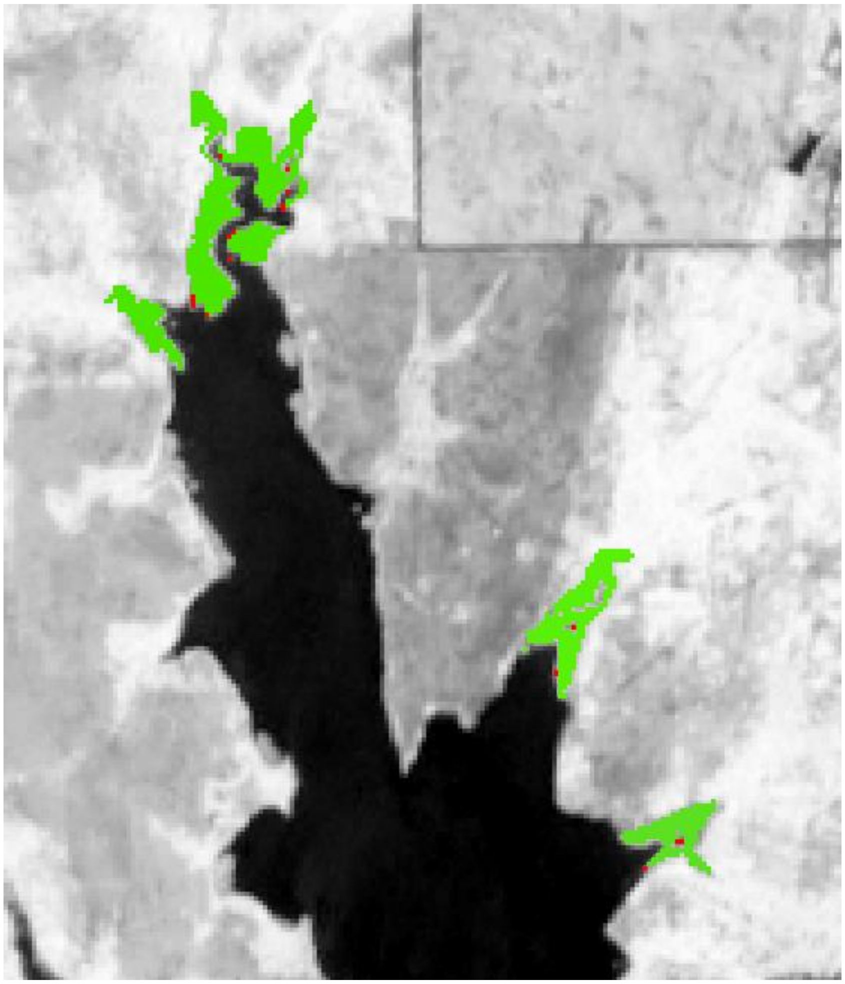

Figure 1: NDVI results from May 30th, 2018, threshold of 0.33 used.

Figure 2: NDVI results from May 30th, 2018, threshold of 0.365 used.

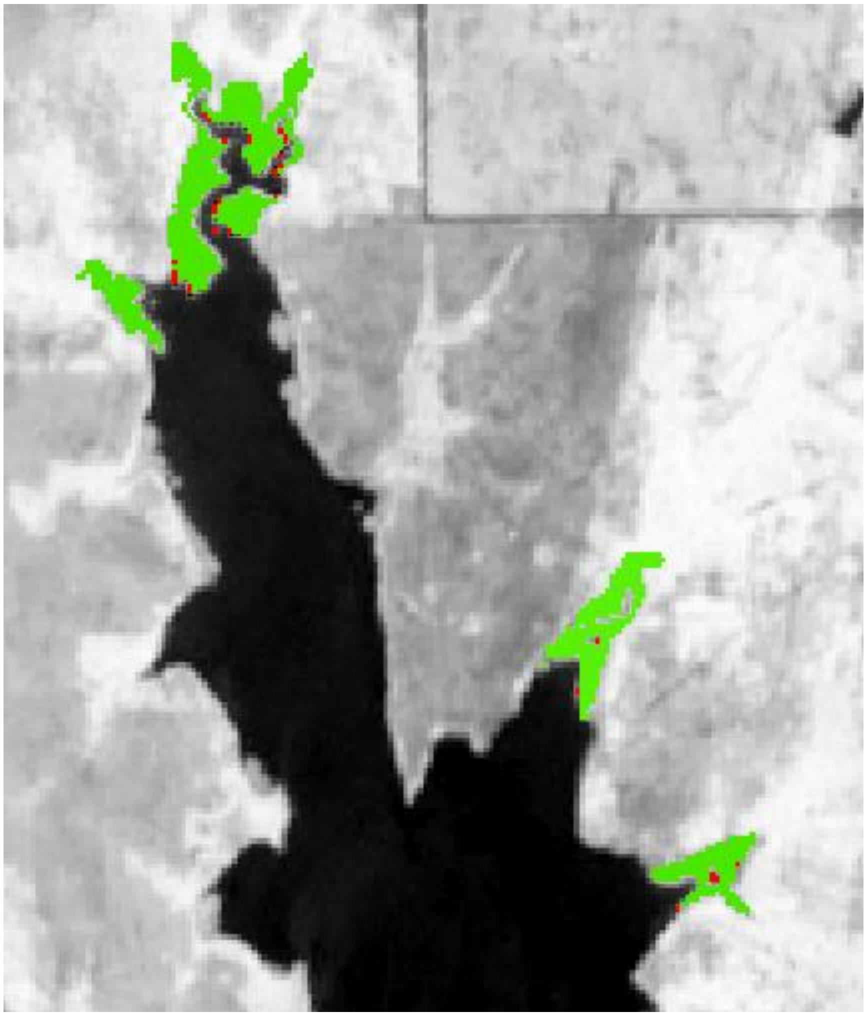

Figure 3: NDVI results from May 30th, 2018, threshold of .4 used.

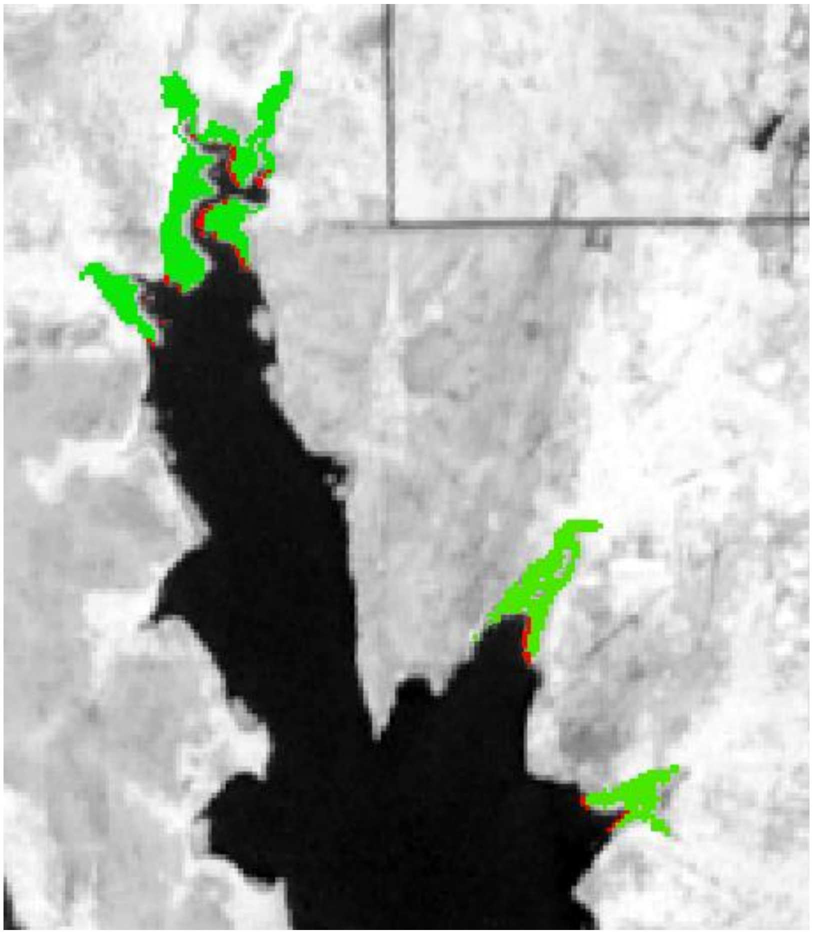

Figure 4: NDVI results from June 14th, 2018, threshold of 0.33 used.

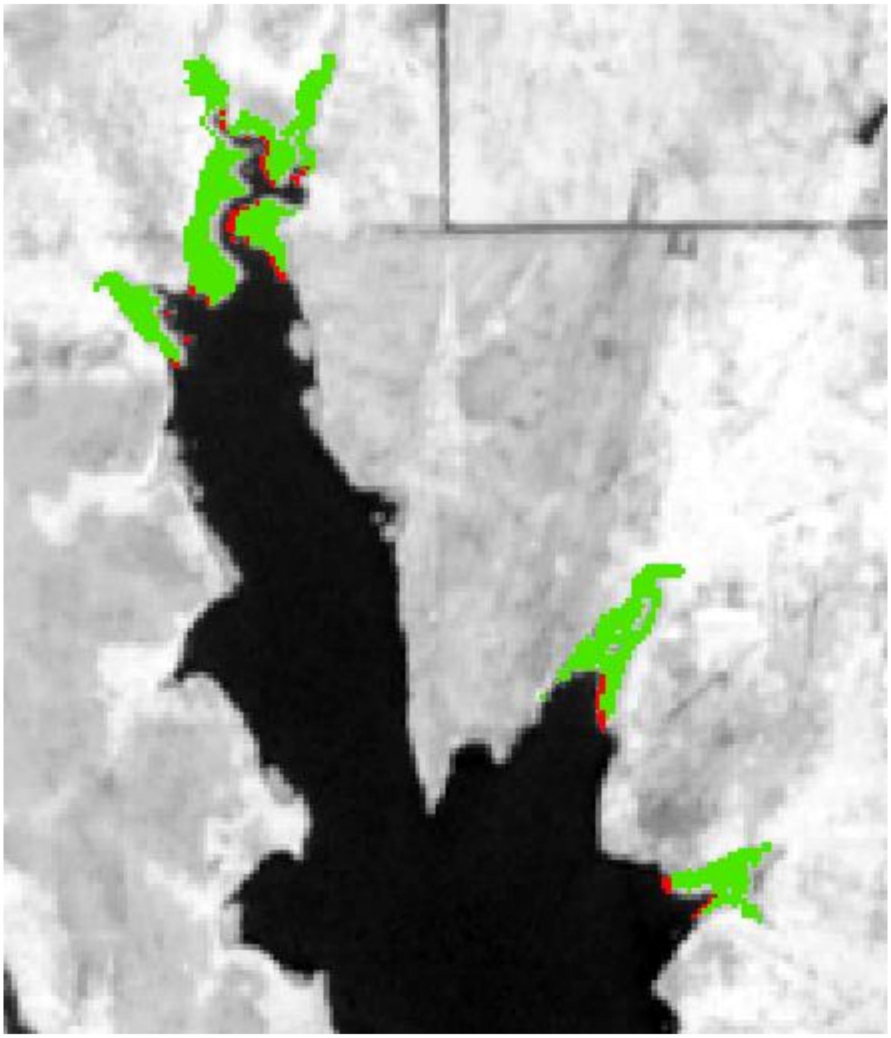

Figure 5: NDVI results from June 14th, 2018, threshold of 0.365 used.

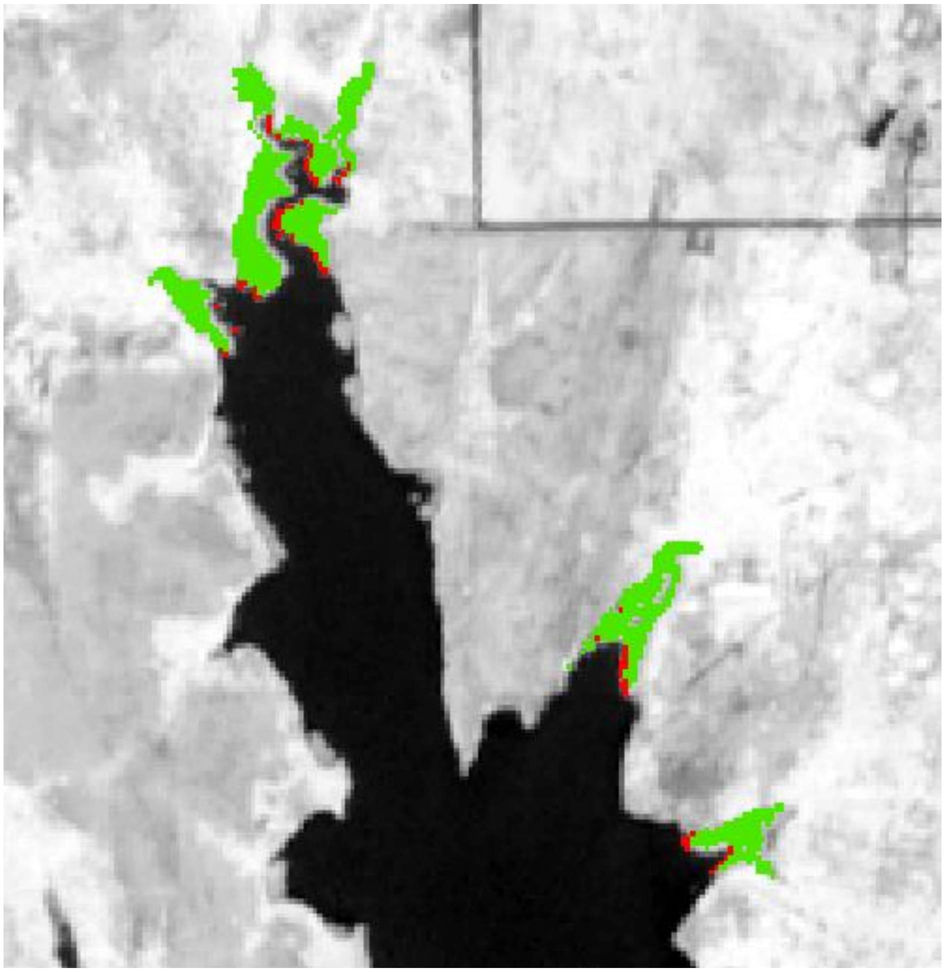

Figure 6: NDVI results from June 14th, 2018, threshold of 0.4 used.

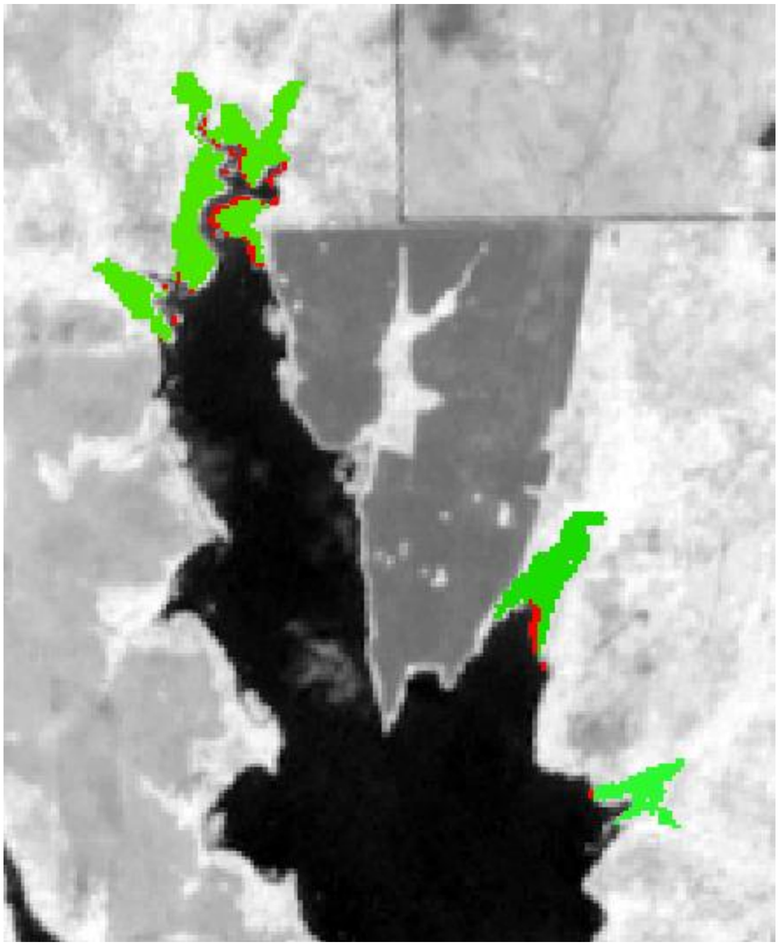

Figure 7: NDVI results from September 2nd, 2018, threshold of 0.33 used.

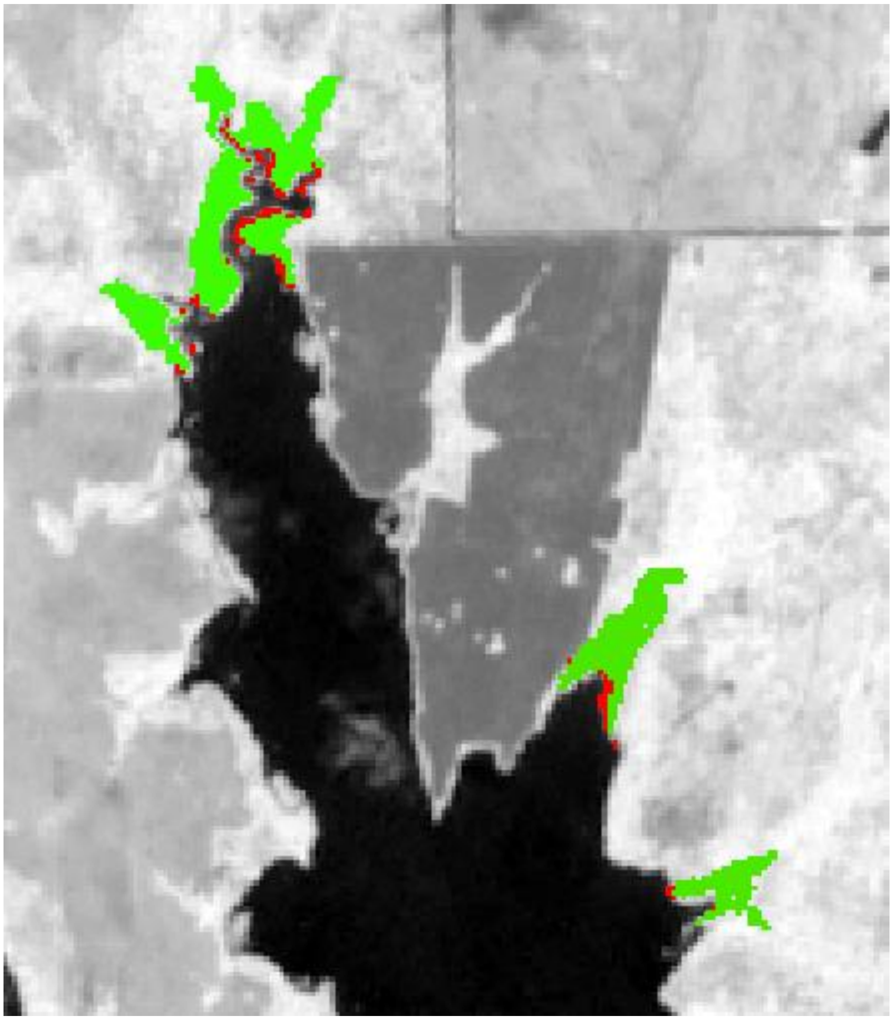

Figure 8: NDVI results from September 2nd, 2018, threshold of 0.365 used.

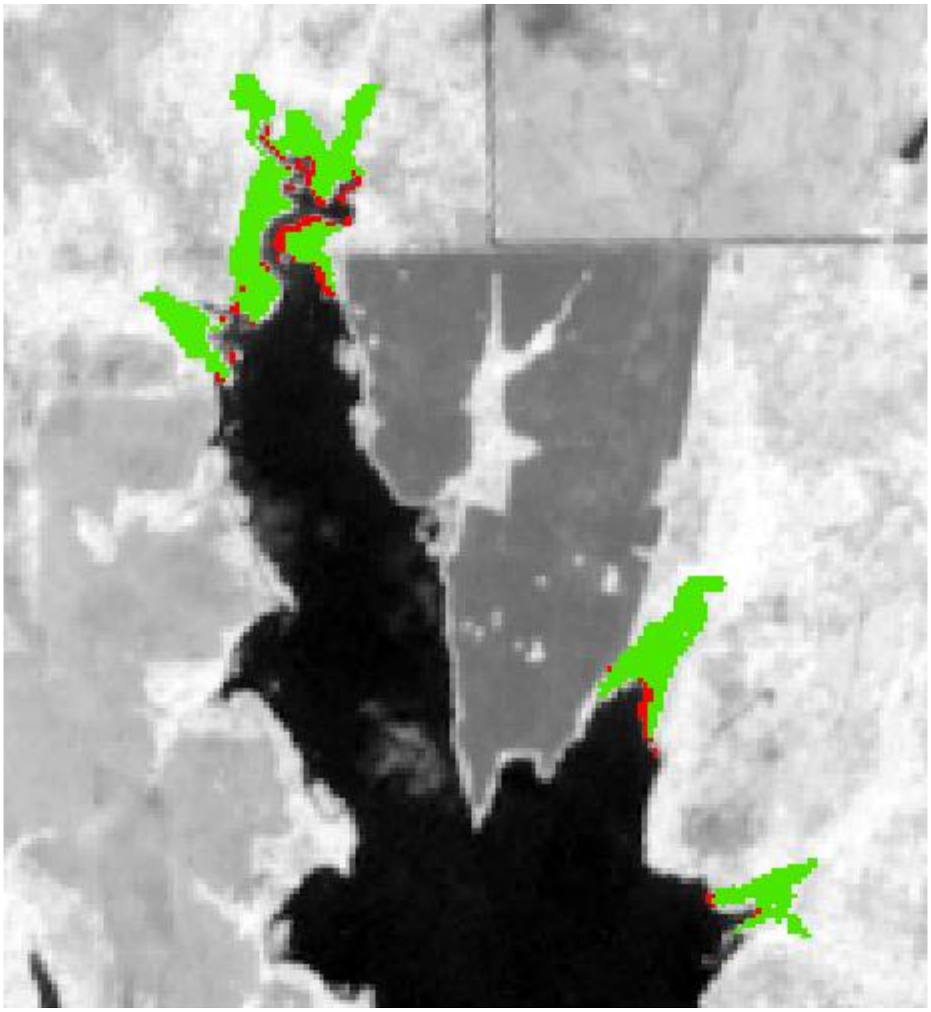

Figure 9: NDVI results from September 2nd, 2018, threshold of 0.4 used.

Appendix B

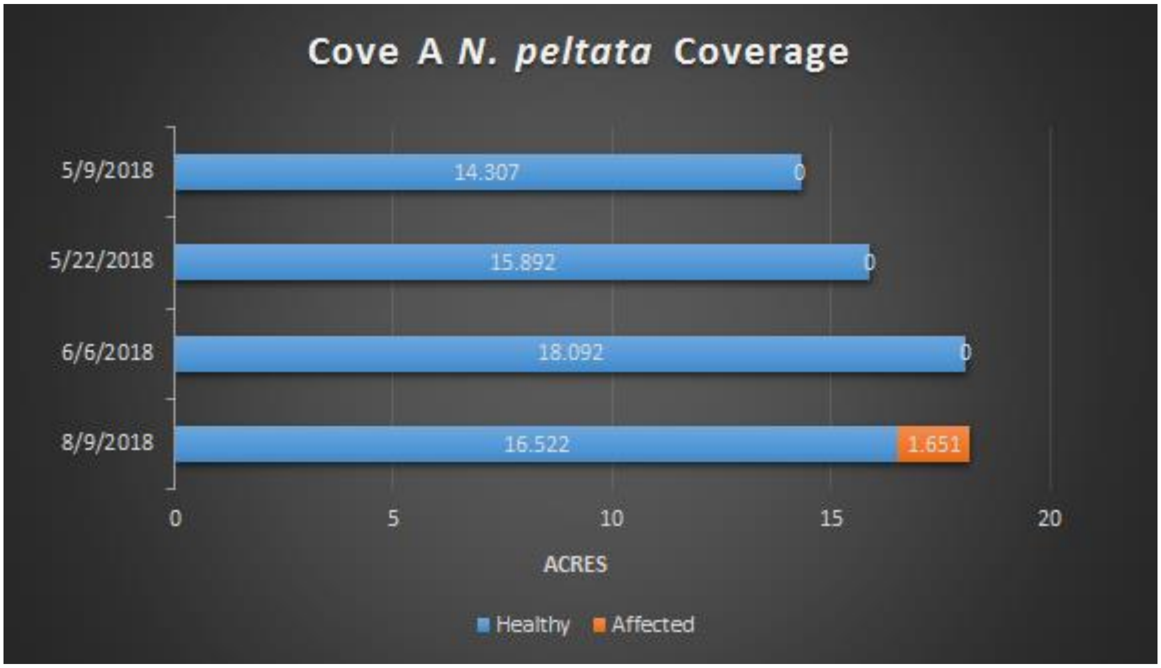

Figure 1: Cove A *N. peltata* coverage over the 2018 growing season.

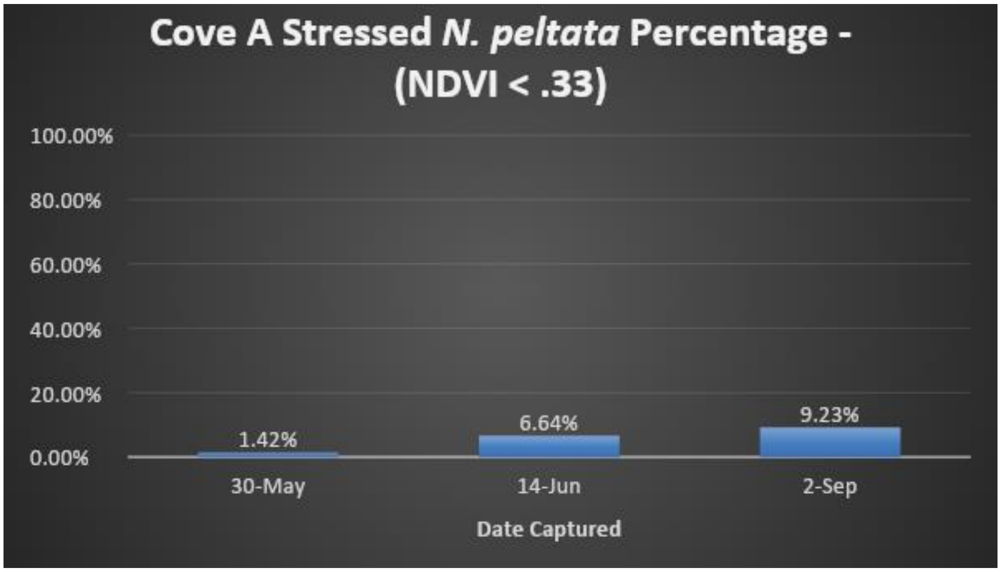

Figure 2: Cove A stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.33.

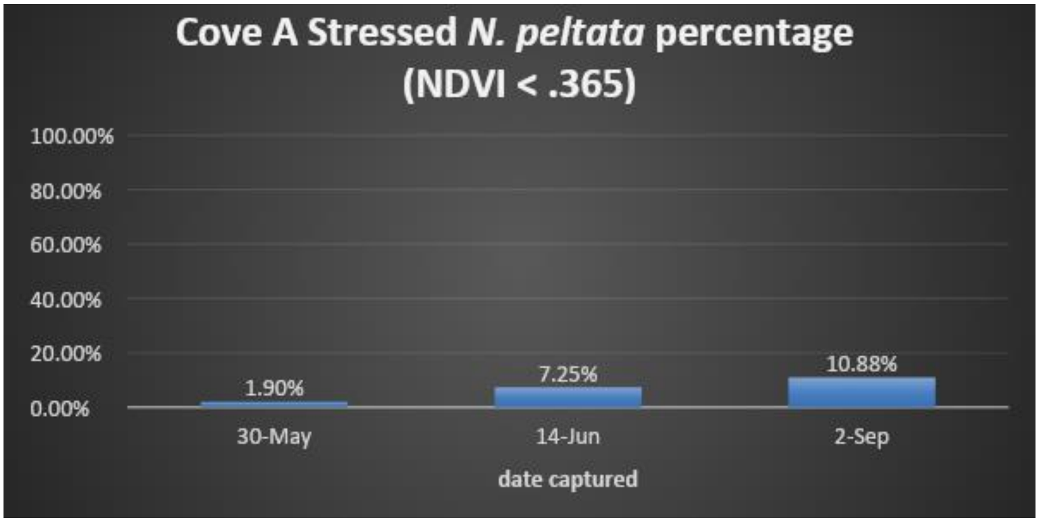

Figure 3: Cove A stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.365.

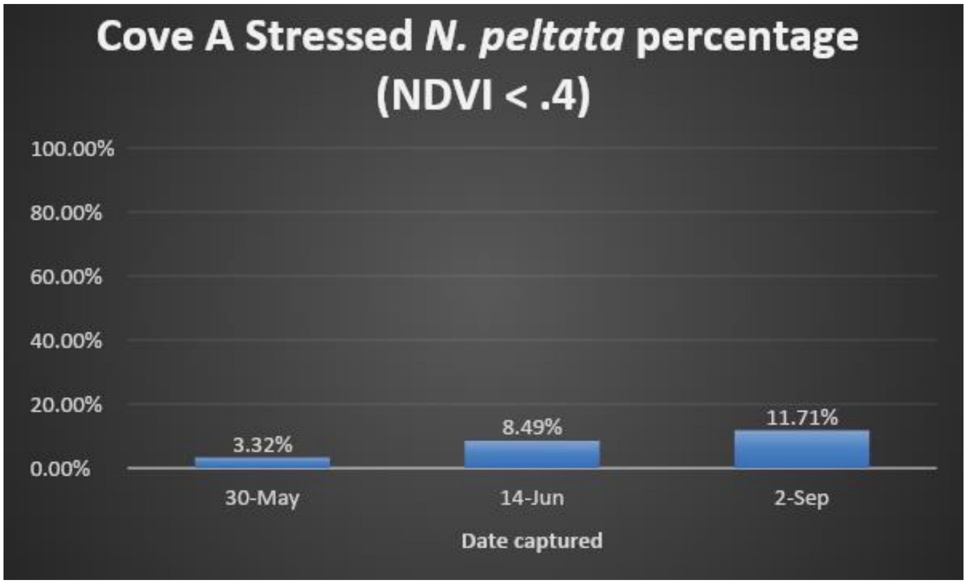

Figure 4: Cove A stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.4.

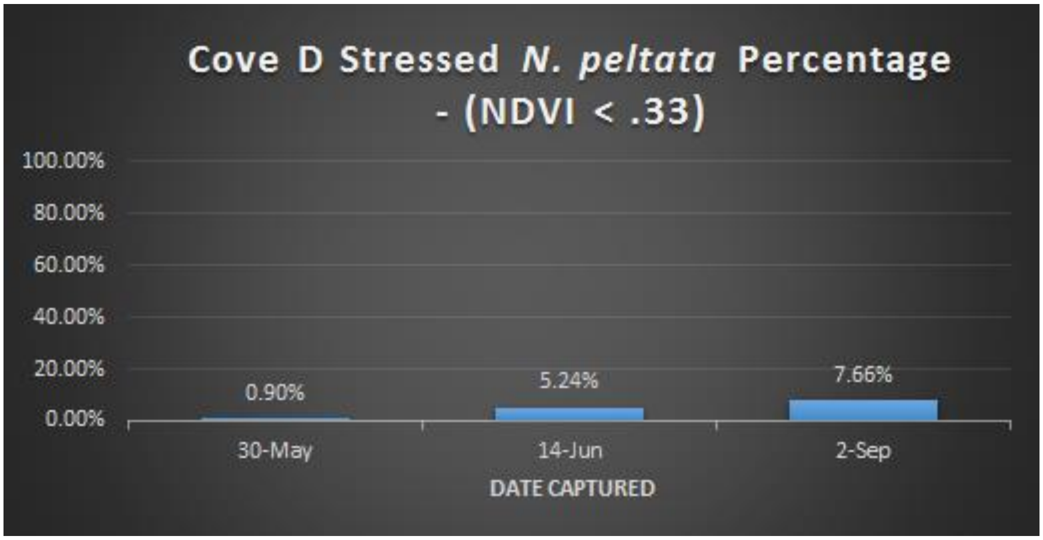

Figure 5: Cove D stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.33.

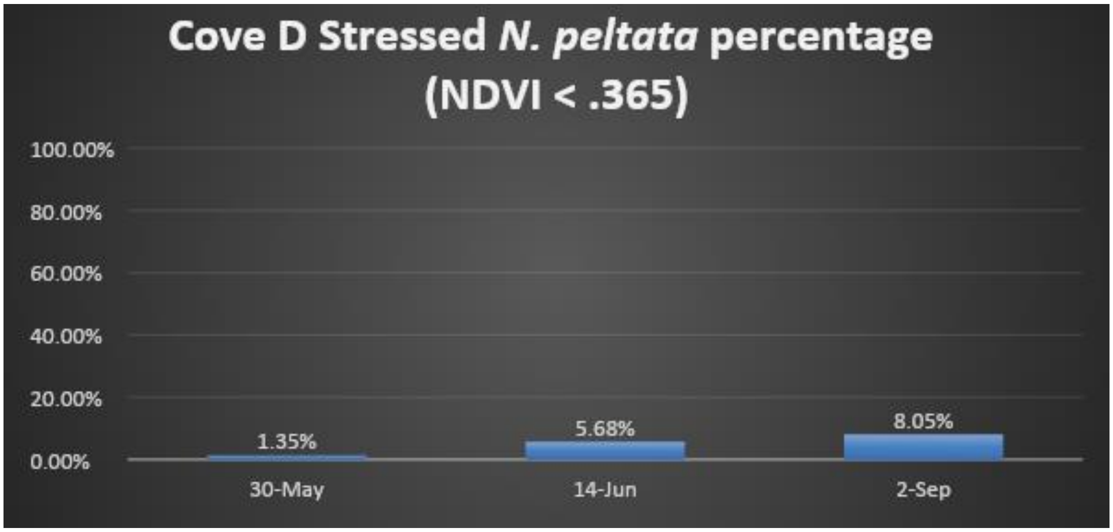

Figure 6: Cove D stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.365.

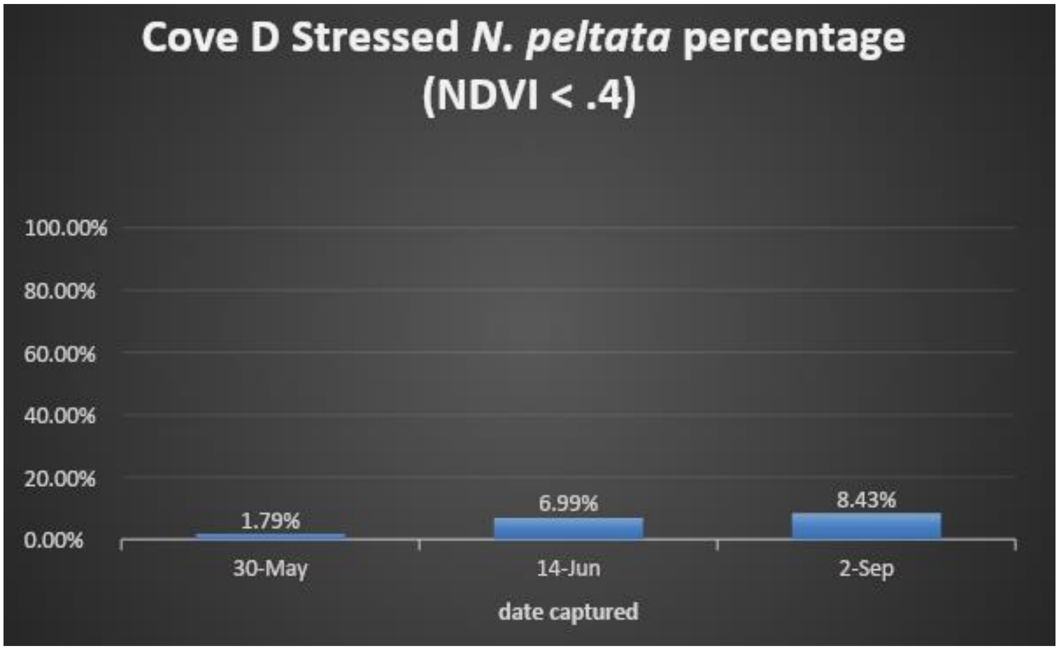

Figure 7: Cove D stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.4.

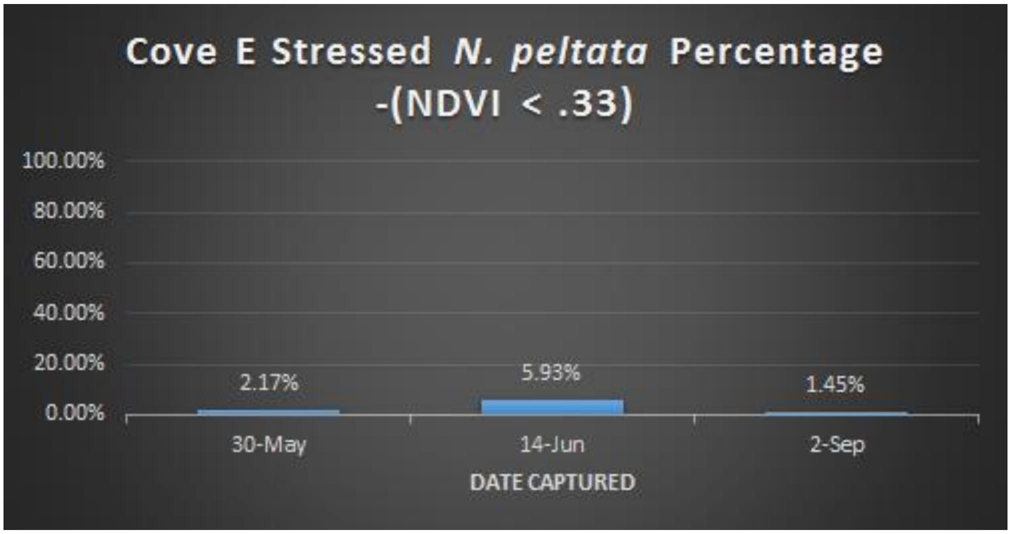

Figure 8: Cove E stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.33.

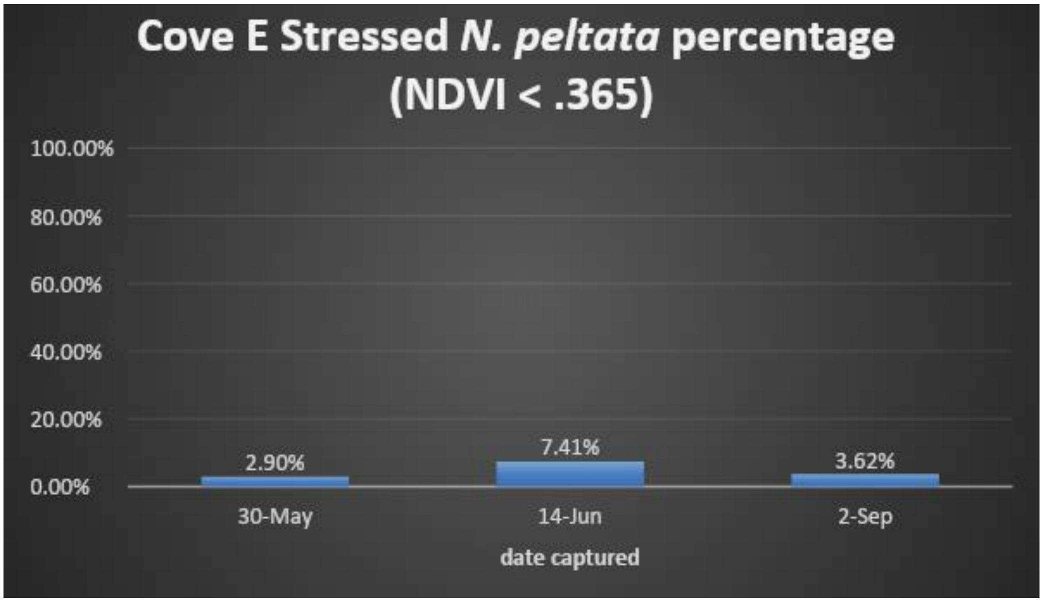

Figure 9: Cove E stressed *N. peltata* coverage as a percentage with NDVI threshold of 0.365.

VITA

Stephen Angle

Candidate for the Degree of

Master of Science

Thesis: MONITORING YELLOW FLOATING HEART (*N. PELTATA*) ON LAKE CARL BLACKWELL VIA REMOTE SENSING

Major Field: Environmental Science

Biographical:

Education:

Completed the requirements for the Master of Science in your major at Oklahoma State University, Stillwater, Oklahoma in July, 2019.

Completed the requirements for the Bachelor of Science in your major at Oklahoma State University, Stillwater, Oklahoma in 2017.

Experience: Graduate Research Assistant 2017-2019

Professional Memberships: Society of Environmental Scientists