EFFECTS OF HERBICIDE TREATMENT ON THE INVASIVE YELLOW FLOATING HEART AND WATER QUALITY IN AN OKLAHOMA RESERVOIR

By

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Bachelor of Environmental Science

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Fayette, Missouri

2017

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July 2020

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ACKNOWLEDGEMENTS

This research could not have been possible without the continuous help and support from family, friends, and colleagues. A special thank you to my wonderful friends Stephen Angle, Caleb Biles, Meghan Martin, and Abby McCrae for the assistance in the field and classroom. Finally thank you to my committee for the opportunity, knowledge, and advice I have been given along the way.

Name: BENJAMIN T LAMB

Date of Degree: JULY 2020

Title of Study: EFFECTS OF HERBICIDE TREATMENT ON THE INVASIVE
YELLOW FLOATING HEART AND WATER QUALITY IN AN
OKLAHOMA RESERVOIR

Major Field: ENVIRONMENTAL SCIENCE

Abstract: Effective treatment options are needed to manage and control aquatic invasive plants. Yellow floating heart (*Nymphoides peltata*, YFH) is an aquatic, floating leaf plant that is native to Eurasia and the Mediterranean. It successfully invaded the United States in 1882 and it was first detected in Lake Carl Blackwell (LCB), OK in 2014. It reached a peak coverage of more than 50 acres in 2019. A new reduced risk herbicide called Procellacor™ (florpyrauxifen-benzyl) was used to treat YFH in LCB in July of 2019. The major objectives of this research were to: 1) monitor the effectiveness of the herbicide treatment on YFH in an infested cove of LCB using *in-situ* sample plots, and 2) determine if the treatment affected water quality immediately and then for six weeks following treatment using *in-situ* water quality monitoring and laboratory biological oxygen demand (BOD) bioassays. It was hypothesized that Procellacor™ would cause a die off of YFH, which in turn would increase BOD and reduce dissolved oxygen (DO) concentrations in the cove. Secondary objectives included an assessment of YFH pre-treatment plant coverage distributions in relation to water depth to determine where YFH can potentially spread throughout LCB. A summarization of treatment efforts on YFH in LCB over the past three years was also developed to aid in the future management of YFH in invaded reservoirs. The coverage of YFH was reduced to 0% within four weeks after treatment. The effects of treatment on BOD and DO were generally short lived and not significant. Biological oxygen demand increased at some of the sample plots as plant decay occurred while DO concentrations increased in areas that had low concentrations before treatment, as water cycling increased. Turbidity also increased at all sites by the end of the sampling period. The results of this research suggest that Procellacor™ can effectively control YFH in a relatively large reservoir and that the post-treatment impacts to water quality are relatively minimal and short lived.

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CHAPTER I

INTRODUCTION

Aquatic invasive species impact ecosystems throughout the world. Invasive species have been introduced into new habitats at increasing rates due to worldwide trade and travel (Johnson et al., 2001). These introductions are often influenced by human activities such as international shipping which transports aquatic organisms across the world in their ballast water, and smaller boats which transport them in their live wells, propellers, and trailers (Lovell et al., 2006). Aquatic invasive species can act as ‘ecosystem engineers’ and alter ecosystems through large-scale and widespread changes in water quality and the cycling of nutrients and organic matter (Jones et al., 1996).

Aquatic invasive plants are of particular concern because they cause both severe ecological and economic damages (Lovell et al., 2006). They have the potential to negatively affect aesthetics, drainage, fishing, water quality, fish and wildlife habitat, flood control, human and animal health, hydropower generation, irrigation, navigation, recreation, and land values when established in new ranges (Wersal & Madsen, 2012). Aquatic invasive plants often go unnoticed at first, but by the time they are perceived as problematic they are extremely difficult to eradicate and their harmful ecological impacts may be irreversible (Les & Mehrhoff, 1999). The estimated total cost of management and losses due to invasive aquatic plants in the United States alone is approximately $110 million per year (Pimentel et al., 2005).

Effective management strategies are needed to help reduce the ecological and economic influences of aquatic invasive plants and reduce their spread into new habitats. Chemical treatment using herbicides is widely employed by aquatic plant managers in both private and public water bodies throughout the United States (Netherland, 2014). Chemical treatment may have indirect negative effects on the water quality of infested waterbodies. The control of vegetation with herbicides can result in a temporary increase in biological oxygen demand (BOD), which is a measure of how much oxygen is used by microorganisms such as bacteria (Winton et al., 2019). This is most likely to occur in eutrophic systems with high macrophyte biomass and low reaeration rates (Jewell, 1971; Almazan & Boyd, 1978). Organic material is released as large mats of aquatic vegetation rapidly die following chemical treatment. This material is then broken down by bacteria causing a decrease in water column dissolved oxygen (DO) concentrations during and after plant death. Atmospheric reaeration cannot offset the increase in oxygen consumption during decomposition in dense macrophyte stands (Greer, 2014). Complete deoxygenation in the water column can occur within one week of chemical herbicide application (Jewell, 1971).

Typical sources of BOD in the water column are biodegradable organic carbon and ammonia that are common constituents or metabolic byproducts of decaying plant materials (Penn et al., 2009). The increase in BOD following chemical treatment depends in part on how much plant biomass is killed and how fast, water temperatures during and after the chemical application, and lake depth and volume of the treatment area (WDNR, 2006). Increased BOD can result in fish kills due to low DO concentrations (Jewell, 1971; Brooker & Edwards, 1975). BOD levels should begin to decline, and water column DO concentrations may return to pre-vegetation die off levels over time, as the organic material is consumed by bacteria and dispersed through the water (Penn et al., 2009). It is often anecdotally assumed that DO decreases and BOD increases following chemical treatment of aquatic plants (Islam, 2019), research-based studies on the relationships between chemical treatment, DO, and BOD are scarce in scientific literature.

The aquatic lily Nymphoides peltate is commonly referred to as yellow floating heart (YFH) or fringed water lily. It is an example of an invasive aquatic plant that negatively impacts native ecosystems (Figure 1). Yellow floating heart is native to Eurasia, the Mediterranean, China, India, and Japan (NWCB, 2007).

Yellow floating heart has been used as an ornamental plant and intentionally released throughout the world and was first recorded in the United States in 1882 (Nault & Mikulyuk, 2009). Yellow floating heart has been repeatedly introduced since its initial use as an ornamental plant. It has been sold over the internet, increasing its ability to travel to all parts of the world. Spread then occurs through the accidental flooding of ponds into surrounding waterways or hitchhiking with other species ordered through water garden catalogs (Nault & Mikulyuk, 2009). Yellow floating heart has been reported in 32 states in the United States and is prohibited in Illinois, Michigan, and Wisconsin (USGS, 2019).

Yellow floating heart is effective at dispersing to other waterbodies and successfully establishing new populations. It often becomes the dominant plant species in locations where it has been established because it outcompetes and displaces native species (Brock et al., 1983). Yellow floating heart has the potential to colonize large areas within a single growing season because each plant can produce over 100 new plants in as little as 12 weeks (Zhonghua et al., 2007). It can grow in depths up to approximately 3m, but it is most frequently found at depths between 1 to 1.5m. The average coverage tends to increase with depth (Van der Velde et al., 1979). Yellow floating heart grows in dense mats (Figure 2), which can cause many negative effects on local species, native biodiversity, and water quality. Yellow floating heart reproduces prolifically by vegetative and sexual means. It can reproduce by seeds, stolons, rhizomes, and broken off leaves with part of their stem remaining, making it very difficult to control. Boat or recreational uses that break off leaves can lead to spread within and between waterbodies (Nault & Mikulyuk, 2009).

A weed risk assessment by the United States Department of Agriculture ranked YFH high for impact and spread potential in the United States (USDA, 2012). Yellow floating heart affects habitats and reduces biodiversity by competing and displacing native vegetation. Its dense mats can outcompete submerged vegetation for light and can alter the chemical composition of the waterbody by increasing organic material and nutrient concentrations (Haug, 2018). Yellow floating heart absorbs large amounts of nutrients from the sediment during growth and then releases it back into the water column during decomposition (Josefsson & Andersson, 2001).

The large, dense mats of YFH can also decrease aesthetic value and alter an ecosystem by displacing native species or creating stagnant areas with low oxygen (Nault & Mikulyuk, 2009). The influences of YFH can result in reductions in tourism by hindering recreational activities such as boating, fishing, swimming, or water skiing. These impacts could ultimately result in reductions in waterside property values (Robinson, 2004).

Procellacor™ is a new proprietary herbicide that has shown high efficacy for controlling invasive aquatic plant species in the United States. These include hydrilla, watermilfoil and YFH (Netherland & Richardson, 2016). The active ingredients in Procellacor™ include florpyrauxifen-benzyl: 2-pryridinecarboxylic acid, 4-amino-3-chloro-6-(4-chloro-2-flouro-3-methoxy-phenyl)-5-flouro and phenyl methyl ester (EPA, 2018). It is a post-emergent, synthetic auxin herbicide for selective control of susceptible grass, sedge, and broadleaf weeds. Synthetic auxin herbicides affect plant specific processes and are easily absorbed and translocated throughout sensitive plants. They are generally selective to control dicots, with minimal impacts to monocots (Epp et al., 2016;

Grossman, 2010; Netherland, 2009). This herbicide is part of a new class of synthetic auxins that differ in binding affinity compared to currently registered auxins (Beets & Netherland, 2018). Procellacor™ has been labelled by the United States Environmental Protection Agency (EPA) as a reduced risk herbicide and there are no drinking water use limitations, no raw water intake setback requirements, and it works best when applied under the surface (EPA, 2018).

Haug (2018) applied florpyrauxifen-benzyl to the isolated shoot tissue of ten different aquatic plants to determine absorption and translocation patterns. All the tested species showed evidence of translocation including *Nymphoides cristata* (crested floating heart), which is a close relative of YFH. Initial work also suggests that Procellacor™ is effective at treating invasive plant infestations. Beets and Netherland (2018) tested short-term exposure scenarios on the invasive species *N. cristata* and *Hydrilla verticillata* (hydrilla) in outdoor mesocosms to determine initial activity and selectivity. Their results confirm that florpyrauxifen-benzyl was effective at label concentrations. Exposure time in all treatments had a significant effect on plant biomass, with an 89% reduction during a 24-hr exposure, 100% reduction during a 72-hr exposure, and 99% reduction during a static exposure at 12 µg L-1.

Procellacor™ has also produced similar results on YFH infestations in smaller waterbodies. A small pond in North Carolina with a one-acre infestation of YFH was treated with Procellacor™. Most of the plant biomass was killed within 44 days of treatment and 100% efficacy was observed within 105 days of treatment (Heilman et al., 2018). Moss Reservoir (1,140 acre) in Texas was treated for YFH with Procellacor™ in 2018, after failed attempts with other herbicides in previous years. They saw a reduction from 9 acres in spring 2018 to 3.4 acres in spring 2019 (District et al., 2019).

Chemical treatment of invasive plants is expensive and needs to be done efficiently to save time and money while making the most of control efforts. Knowing the potential distribution of an aquatic plant within a waterbody could be useful for developing site-specific treatment plans. Aquatic plant distributions are generally influenced by water depth due to light availability, nutrient sources, and pressure (Godshalk & Wetzel, 1978). Riis et al. (2012) studied the effects of light availability on the initial establishment of three invasive aquatic plants. Light availability had a strong effect on growth rate and plant morphology for all species. Relative growth rates of all three species increased approximately three-fold from low to high light availability. In most freshwater ecosystems, vascular plants are reported to be limited to regions less than 5m in depth and are limited to less than 2m in lakes with poor water clarity (Sculthorpe, 1967).

In small, shallow systems, depth may not limit the growth of YFH. The entire waterbody may need to be chemically treated in such systems. Depth can vary considerably within a large reservoir system (e.g. lacustrine, transition, and riverine zones). The distribution of YFH can be restricted to certain areas in these larger systems.

Knowing which areas are potentially suitable for YFH will be important for developing site specific management plans. Reservoir bathymetry can help guide treatment efforts by identifying specific locations where YFH is most likely to grow based on water depth.

Weisner (1991) suggests basing models predicting distribution of emergent macrophytes on the plant's capability for water depth penetration. Remillard and Welch (1993) compared predicted vegetation with actual vegetation distributions which indicated that only water depth and sedimentation data layers were necessary for predicting more than 90% of emergent and submergent distributions. The bathymetry of a system can be used by managers to identify the potential distribution of YFH, which is found in depths up to 3m (Van der Velde et al., 1979), to better target treatment to save money and reduce herbicide exposure.

The purpose of this research was to monitor the effectiveness of the herbicide (Procellacor™) treatment on YFH in an infested cove in Lake Carl Blackwell (LCB), which is a drinking water reservoir near Stillwater, OK. *In-situ* plots were used to determine 1) the effectiveness of Procellacor™ in reducing the surface coverage of YFH, and 2) DO and BOD changes immediately after treatment and then over the next six weeks post-treatment. I hypothesized that Procellacor™ would cause a die off of YFH, which in turn would increase BOD and reduce DO concentrations in the cove. A second objective was to assess YFH pre-treatment coverage distributions in relation to depth, to determine where YFH can potentially spread throughout LCB. A third objective was to summarize treatment efforts of YFH in LCB over the past three years and to address the success and relative cost of different treatment options to develop a guide to aid in the future management of YFH in invaded reservoirs. This summarization of previous treatment efforts can be found in the appendices.

CHAPTER II

METHODS

Field Sampling

Field sampling on LCB began on 7/2/19 prior to application of Procellacor™. Procellacor™ was applied by a certified applicator on 7/9/19-7/10/19. I selected one infested cove, known as Cove D, on the north side of LCB to monitor before treatment and then weekly for six weeks after treatment (Figure 3). This cove was selected due to its dense growth of YFH, accessibility from land, and navigability by canoe. It also had an established infestation of YFH over at least the past two growing seasons (Angle, 2019). Sampling took place at approximately the same time of the day (~10:00 am) each week so that diurnal effects of plant flowering and oxygen concentrations did not differ between sampling dates.

Seven sample plots were established in the cove (Figure 4). One sample plot (Site 1) was located in open water near the mouth of the cove where YFH did not grow. This open water site was used to determine the water quality conditions, including BOD, in the reservoir in the absence of YFH. The other six sampling points were located along the west side of the cove at roughly evenly spaced intervals to the back of the cove. These six sample plots were in areas infested with YFH vegetation. The coordinates of each sample location were marked using a GPS so that they could be revisited and sampled via canoe.

A 1m x 1m quadrat made from PVC was used to visually assess the health of YFH at each site. The quadrat was used four times at each sampling point at the four corners of the canoe. Data was recorded for three different variables in each quadrant, which was quantified/counted visually: the number of bloomed flowers, the percentage of leaf surface coverage and the percentage of those leaves that were visibly stressed by the Procellacor™ treatment, based on color and visible plant decay.

A multi-parameter YSI brand Pro DSS probe was used at each of the seven sampling sites for DO (mg/L) and turbidity (Formazin Nephelometric Unit, FNU). Triplicate water samples were also collected just below the surface in 500 ml brown bottles at each of the seven sample points and taken to the lab at Oklahoma State University for measurements of DO and BOD testing within 2 hours of collection. This data was compiled, organized and stored using Microsoft Excel.

Lab Sampling

The 21 water samples were transferred into individual plastic BOD testing bottles (300 mL) in the laboratory on each sampling day. A YSI brand Pro series, self-stirring oxygen probe was attached to the Pro DSS meter and used to measure the initial DO concentration in each BOD bottle (mg/L DO). The BOD bottles were then sealed with acrylic stopper caps and were incubated in the dark at the testing standard of 20°C for five days to allow DO to be consumed by the microorganisms in the water sample (Jouanneau, et al. 2014). The bottles were removed after five days and DO was measured again using the probe. Biological oxygen demand (BOD in mg/L) was determined by subtracting the day 5 DO readings from the day 1 DO readings for each bottle.

T-tests were used to determine if there were significant changes in DO and BOD at each site before and after treatment for each sampling date. These tests were conducted using a t-test calculator at graphpad.com. The pre-treatment measurements at each site served as a control and were compared to each subsequent sampling event at that site. A Bonferroni corrected p-value was used to account for the five t-tests that were conducted for each variable at a given sample site ($P=0.05/5=0.01$).

Depth Distribution

Limited bathymetry data were available for LCB that did not include Cove D. Sentinel-2 satellite imagery of LCB was used to compare YFH coverage and distribution with known depths around the lake using the partial bathymetry data. Depths from 0-3m were highlighted and overlaid on aerial imagery of pre-treatment peak YFH growth on Lake Carl Blackwell (6/29/2019) using ArcMap 10.6. These depth contours overlaid on the aerial imagery were used to better understand how depth influenced YFH coverage and distribution in LCB.

CHAPTER III

RESULTS

Yellow Floating Heart Coverage

Site 1 was located in open water near the mouth of Cove D. It was the deepest site (~2m) and YFH was never present at this site during sampling. Sites 2-7 all had YFH with flowers at the start of the treatment on July 9-10th, 2019. Site depth decreased further back from the mouth of the cove and varied between 0.2 and 2.0m. Sites 5-7 were the shallowest sites (~0.5m) and were located in the back of the cove.

Sites 2, 3, 4 and 5 all had close to 100% surface coverage of YFH on 7/2/2019, before treatment (Figure 5). Sites 6 and 7 had 70% and 40% surface coverage on 7/2/2019, respectively. Submerged mats of plant material were present throughout most of the water column at both sites.

All the sites treated with YFH showed a decrease in surface coverage the week following Procellacor™ treatment, except for Site 7. This site saw an increase of nearly 20% (Figure 5). All flowers were gone by the first sampling event after treatment on 7/12/2019. Site 6 had significantly less coverage one week following treatment (Figure 5 and Table 1). All the sites experienced a significant, sharp decrease in coverage by week 3 (Table 1). They dropped below 10% by week 3 and almost 0% by week 4 (Figure 5).

All sites remained at 0% surface coverage throughout the sampling season. There were a few new, singular leaves that emerged at Sites 3 and 4 on week 6. These leaves accounted for less than 2% of surface coverage (Figure 5).

Dissolved Oxygen

Site 1 had the highest DO concentrations. Pre-treatment levels were just below 8 mg/L, where they remained throughout the sampling and there were no significant differences between pre- and post-treatment dates (Figure 5; Table 2).

Dissolved oxygen responded differently to treatment based on the position of the site in the cove where YFH was present. The three middle sites (2-4) responded relatively similarly to treatment. Dissolved oxygen at these sites was just below 6 mg/L before treatment. Dissolved oxygen then increased after treatment for the next three weeks, peaking around 8 mg/L in week 4. Site 2 experienced significantly higher levels in weeks 3, 4, 6 and 7 compared to pre-treatment concentrations (Table 2). Site 3 experienced significantly higher DO levels in weeks 4 and 7 (Table 2). Site 4 also experienced significantly higher levels in weeks 4, 6 and 7 (Table 2). Dissolved oxygen concentrations were significantly higher at the end of the sampling compared to pre-treatment concentrations at each of these three sites (Figure 5; Table 2).

The three sites that were located the furthest back in the cove (5-7) also responded similarly to treatment. Dissolved oxygen in these shallower sites was ~ 4 mg/L or less before treatment. Dissolved oxygen then decreased to 1-2 mg/L in the sampling event two days after treatment, although these decreases were not significantly lower than pre-treatment concentrations (Figure 5; Table 2). Dissolved oxygen then sharply increased for the next two weeks, peaking around 7-8 mg/L in week 4, the same week that DO peaked at all seven sites. The final DO levels in these sites was similar to those in the deeper sites. Site 5 was the only shallow site that had any significant differences, with DO significantly higher in sampling weeks 2, 4, 5, 6 and 7 compared to pre-treatment concentrations (Figure 5; Table 2).

Biological Oxygen Demand

Biological oxygen demand also responded differently to treatment based on the sample site location. Biological oxygen demand at Site 1 initially experienced a significant decrease, dropping from ~2 mg/L during pre-treatment to ~1 mg/L two days after treatment (Figure 5, Table 3). Biological oxygen demand then slowly increased the following weeks and stayed relatively consistent with pre-treatment levels throughout the remainder of the sampling (Figure 5).

Sites 2-4 showed an increase in BOD the week after treatment (week 2), reaching levels near 4 mg/L. All three sites showed decreases the following week (week 3) to near pre-treatment levels of 2 mg/L. Biological oxygen demand remained fairly constant for the remainder of sampling with temporary rises in week 5. It is important to note that there was no significant difference between pre- and post-treatment BOD levels at any of these three sites (Table 3).

Biological oxygen demand in sites 5-7 decreased in the week immediately following treatment. BOD increased to levels higher than before treatment for week 3, then declined slowly for the remainder of sampling. Similar to sites 2-4, there were no significant differences between pre- and post-treatment BOD levels (Table 3).

Turbidity

Turbidity remained low throughout treatment at Site 1 (~10 FNU). Most of the sites with YFH had pre-treatment turbidity levels that were similar to the control site between 10-15 FNU, with the exception of site 5 which was ~30 FNU (Figure 6). All the infested sites then experienced a relatively consistent increase in turbidity over the course of sampling. The shallow sites experienced greater changes. Week 6 turbidity concentrations for sites 2-7 were the highest of all sampling weeks, ranging between 21-

42 FNU. By the end of sampling (week 7), concentrations were between 10-27 FNU, with sites 2, 3 and 4 concentrations near pre-treatment levels (Figure 6).

CHAPTER IV

DISCUSSION

Procellacor™ was effective at treating YFH in Lake Carl Blackwell. Surface coverage at the 7 sample plots in Cove D was 0% four weeks after a single treatment. Our results are consistent with previous studies showing that florpyrauxifen-benzyl is effective at controlling plants in the family Nymphoides (Beets & Netherland, 2018)

My findings further contribute to the results from treatment in mesocosm studies and smaller waterbodies to show that Procellacor™ can be used to effectively treat infestations of YFH in relatively larger waterbodies. The efficacy that I observed in our sample plots was consistent with the treatment success that was observed throughout LCB. The total YFH infestation in LCB covered a peak total of 55.5 acres in the 2019 growing season based on coverage estimates obtained from satellite imagery (McCrea, 2020). Total YFH coverage on the lake then decreased by 91% within 8 weeks of treatment with Procellacor™ (McCrea, 2020).

Procellacor™ was more effective at treating YFH than previous herbicides that were used in LCB and other waterbodies. Glyphosate was used to treat YFH in LCB in the 2017 and 2018 growing seasons, but it did not stress or reduce YFH coverage (Angle, 2019). Glyphosate was applied three times in Cove D during the 2018 growing season alone. Total YFH coverage in this cove expanded during the treatment period, going from

5.8 acres before treatment to 6.4 acres during this period (Angle, 2019). Measurements of plant stress derived from Sentinel 2 satellite and drone imagery showed that less than 1% of YFH coverage was stressed in the early season and just over 1% was stressed during the peak of the season during treatment in 2018 (Angle, 2019).

The difference in efficacy between glyphosate and Procellacor™ could be due to how the individual herbicides work. Glyphosate must have sufficient contact time with plant tissue before it is diluted or washed off due to wave action. It must be applied directly to surface plant material while the plant is photosynthetically active in order for it to be effective (Getsinger et al., 2008). This can be a problem for aquatic plant control, especially when the target vegetation is floating as opposed to emergent. Glyphosate can take anywhere from 4 to 20 days to kill plant tissue beyond recovery (Henderson et al., 2010), allowing for rainfall, wind, waves, and currents to reduce glyphosate contact time with YFH leaves. Procellacor™ is applied below the water surface where it is absorbed through the root system and targets the plants postemergence (Haug, 2018).

Effects of Herbicide Treatment on Water Quality

The control of vegetation with herbicides can result in a temporary increase in organic matter and BOD with decreases in available DO during and after plant death (Brooker and Edwards, 1973; Newbold, 1975). Dissolved oxygen can then increase over longer periods of time after treatment because the removal of plants decreases respiration and breaks the barrier of floating vegetation, allowing light penetration and increasing wave action and reaeration (Greer, 2014; Jewell, 1971; James et al. 2002). Both of these trends appeared to occur in LCB following treatment of YFH with Procellacor™.

Biological oxygen demand generally increased within the first two weeks of Procellacor™ application. This was presumably due to increased aerobic microbial decomposition of the YFH as it died and decayed (Godshalk & Wetzel, 1978). The initial responses of BOD and DO to treatment varied based on the position of the sample sites in the cove and the DO concentrations at the time of treatment. Sites 2-4 responded relatively similarly to treatment. They experienced increases in BOD the week following herbicide treatment before leveling out for the remainder of the season with no statistically significant changes. Dissolved oxygen at these sites increased following treatment, with significantly higher concentrations observed on most of the final four sampling weeks compared to pre-treatment levels. These sites were located closer to the mouth of the cove with depths greater than 0.5m and had more water cycling occurring and wave action. Greenfield et al. (2007) also found that DO increased after removal of water hyacinth in a wetland that experienced tidal incursions from the adjacent river. This cycled the water, causing DO concentrations to increase after the plant material died. A year-long time series of DO data showed that there were negative relationships between plant abundance and DO concentrations (Greenfield et al., 2007).

Sites 5-7 were shallower (depths of 0.5m or less) and had lower DO concentrations prior to treatment compared to sites 2-4. There was likely little water movement and cycling that occurred in the shallow sites because the submerged plant material was very congested throughout the water column prior to treatment. This could have been due to the water being stagnant, which can cause oxygen to only enter through the top layer of water. This results in low DO concentrations and limits oxygen that is readily available for organisms (Ice & Sugden, 2003).

Floating leaf coverage could also hinder oxygen's ability to enter the water. These sites all experienced a drop in DO and BOD the week following treatment, presumably because there was not enough available oxygen immediately for bacteria to breakdown the YFH as it began to die. Biological oxygen demand and DO levels in these sites then increased, suggesting that plant material in this area began to decompose. The reduction of plant material likely increased water cycling, which replenished DO levels.

Turbidity in Site 1 remained low (~10 FNU) during treatment, showing that no decomposition or resuspension of sediments occurred. Turbidity at all the sites with YFH infestations (sites 2-7) increased after treatment as plant surface coverage decreased to 0%. The absence of plants in aquatic systems can increase turbidity levels because they prevent sediment resuspension and erosion (Horppila & Nurminen, 2005). The presence of macrophytes can reduce sediment resuspension in shallow systems by dampening wave activity and redirecting water currents. James et al. (2002) similarly found after mechanically shredding invasive water chestnut (Trapa natans) that turbidity levels increased over a 14-d period in an experimental station after the plants were removed. These processes likely occurred in LCB as the surface coverage and dense mats of subsurface YFH died and sediment resuspension increased with wave activity (James et al, 2002). These results show that YFH death did influence turbidity, but these changes appear to be minimal and temporary. Other factors such as weather could influence turbidity as well.

Yellow Floating Heart Depth Distribution

Bathymetry data for LCB was incomplete, but there were depth contours for several individual coves in the reservoir. Three of these southern coves and one northern cove had small YFH infestations which were observable from Sentinal-2 aerial imagery (Figures 3 & 8). It was clear from these images that the distribution of YFH was not consistent throughout LCB. Yellow floating heart distribution in the southern coves was generally limited and it was present at shallow depths (0-2m) (Figure 8). Yellow floating heart in the northern coves grew at greater depths that were consistent with literature reported depth preferences and limitations (0-3m) (Figure 7).

Depths between 0-3m (Figure 3) are present along most banks of LCB. The lack of YFH in all these shallow areas suggests that depth is not the only factor that limits YFH growth and spread. It appears to not easily establish near open, moving water and may be limited due to other factors than depth alone (Crossley et al., 2002). These smaller infestations remain close to the shore. This could be due to wind and wave action that can constrain surface coverage. The type of substrate could also play an important role and limit establishment even in areas that are suitable depths. The infestations in the southern coves could also be relatively new compared to Cove D. This could indicate they have had less time to become established and grow to their full extent.

Additional assessment of YFH growth in relation to depth and substrate type should be conducted in these southern coves to better understand the factors influencing establishment. This information could help future management and monitoring efforts by helping to identify which coves are a threat for future spread or could already contain new, unidentified infestations. Understanding where these new infestations occur may help prevent spread and establishment.

CHAPTER V

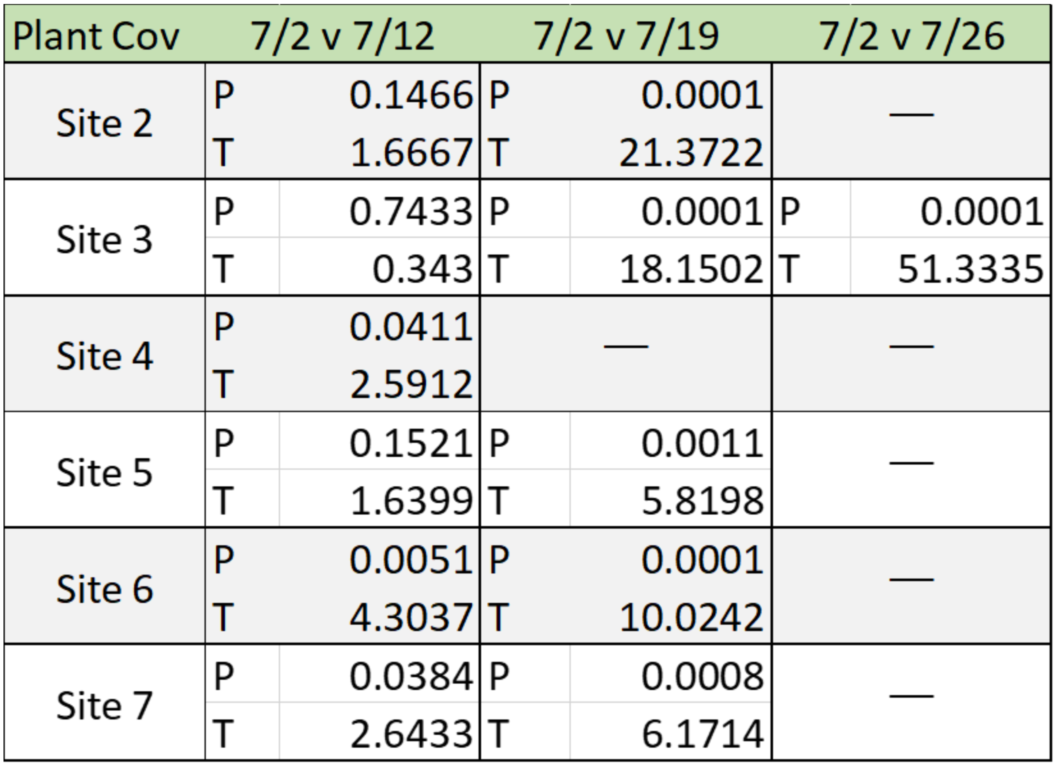
CONCLUSION

Procellacor™ was effective at controlling the YFH infestation in LCB's Cove D during the 2019 growing season. It reduced plant coverage in all sampling sites to 0% four weeks after treatment. Yellow floating heart death and decay only have minimal impacts on BOD and DO following treatment. Biological oxygen demand temporarily increased after treatment, but these differences were not significant and then BOD returned to pre-treatment levels within several weeks of treatment. This rise in concentrations was expected as decomposition occurred but was minimal and did not negatively affect water quality. Dissolved oxygen concentrations increased over time, ending the sampling season with concentrations significantly higher than pre-treatment levels. Depth and water cycling appeared to be important factors that help determine how treatment influenced BOD and DO following treatment.

The distribution of YFH in LCB does not appear to be influenced by depth alone and additional research is needed to better understand where YFH establishes and how environmental factors and substrate types influence its overall distribution in a system (Crossley et al., 2002). The assessment of previous management strategies indicates that there are several viable treatment options (see Appendices). Both hand pulling and benthic matting may be effective for short term control on small infestations. Chemical treatment with Procellacor is the most successful option.

This study provides information on the treatment success and water quality impacts of Procellacor™ that can be used to guide future treatment. Yellow floating heart will most likely require continued treatment efforts in future growing seasons. Understanding which methods are available and when they are most efficient can improve future management results.

TABLES



Plant Cov	7/2 v 7/12		7/2 v 7/19		7/2 v 7/26	
Site 2	P	0.1466	P	0.0001	—	
	T	1.6667	T	21.3722		
Site 3	P	0.7433	P	0.0001	P	0.0001
	T	0.343	T	18.1502	T	51.3335
Site 4	P	0.0411	—		—	
	T	2.5912				
Site 5	P	0.1521	P	0.0011	—	
	T	1.6399	T	5.8198		
Site 6	P	0.0051	P	0.0001	—	
	T	4.3037	T	10.0242		
Site 7	P	0.0384	P	0.0008	—	
	T	2.6433	T	6.1714		

Table 1. T-test results for plant coverage, including P-values and T-values. Sites that reached 0% coverage are not displayed. Degrees of freedom for all is 6. All samples dates (7/12/19, 7/19/19, 7/26/19) were compared against the pre-treatment values (7/2/19 sample date) for each site. Significance was determined using a Bonferoni correct P-value of P=0.01.

DO	7/2 v 7/12		7/2 v 7/19		7/2 v 7/26		7/2 v 8/5		7/2 v 8/12		7/2 v 8/21	
Site 2	P	0.0096	P	0.015	P	0.0705	P	0.013	P	0.0127	P	0.0402
	T	5.9239	T	5.0469	T	2.7544	T	5.377	T	5.3594	T	3.4756
Site 3	P	0.5391	P	0.0001	P	0.0001	P	0.076	P	0.0001	P	0.0001
	T	0.6912	T	29.537	T	43.151	T	2.666	T	33.388	T	26.037
Site 4	P	0.7099	P	0.0131	P	0.0038	P	0.033	P	0.0754	P	0.0062
	T	0.4092	T	5.3014	T	8.1707	T	3.748	T	2.6752	T	6.9113
Site 5	P	0.8954	P	0.0201	P	0.0022	P	0.033	P	0.0284	P	0.0026
	T	0.143	T	4.5335	T	9.9071	T	3.743	T	3.9811	T	9.3064
Site 6	P	0.0073	P	0.9678	P	0.0001	P	3E-04	P	0.0004	P	0.0001
	T	6.5139	T	0.0438	T	30.772	T	20.34	T	18.216	T	30.351
Site 7	P	0.4921	P	0.2013	P	0.0362	P	0.197	P	0.0683	P	0.0246
	T	0.7804	T	1.6314	T	3.6207	T	1.653	T	2.7919	T	4.1994
Site 8	P	0.0753	P	0.7331	P	0.0204	P	0.202	P	0.0771	P	0.0213
	T	2.6757	T	0.3743	T	4.5093	T	1.63	T	2.6489	T	4.438

Table 2. T-test results for dissolved oxygen, including P-values and T-values. Degrees of freedom for all tests is 3. All samples dates (7/12/19, 7/19/19, 7/26/19, 8/5/19, 8/12/19, and 8/21/19) were compared against the pre-treatment values (7/2/19 sample date) for each site. Significance was determined using a Bonferoni correct P-value of P=0.01.

BOD	7/2 v 7/12		7/2 v 7/19		7/2 v 7/26		7/2 v 8/5		7/2 v 8/12		7/2 v 8/21	
Site 2	P	0.0071	P	0.0223	P	0.0296	P	0.387	P	0.1922	P	0.037
	T	6.6083	T	4.3587	T	3.9142	T	1.011	T	1.6767	T	3.59
Site 3	P	0.2879	P	0.5685	P	0.0761	P	0.68	P	0.1392	P	0.1209
	T	1.2887	T	0.6387	T	2.6638	T	0.456	T	2.0011	T	2.148
Site 4	P	0.1282	P	0.2834	P	0.0555	P	0.503	P	0.3053	P	0.0366
	T	2.0868	T	1.3035	T	3.0483	T	0.76	T	1.2333	T	3.6045
Site 5	P	0.3251	P	0.3733	P	0.2745	P	0.682	P	0.2701	P	0.2619
	T	1.174	T	1.0437	T	1.3339	T	0.453	T	1.3489	T	1.3783
Site 6	P	0.2204	P	0.4752	P	0.7709	P	0.796	P	0.92	P	0.6865
	T	1.5434	T	0.8141	T	0.3187	T	0.282	T	0.1092	T	0.445
Site 7	P	0.5301	P	0.6369	P	0.9922	P	0.992	P	0.5737	P	0.3632
	T	0.7077	T	0.5234	T	0.0107	T	0.011	T	0.6295	T	1.0696
Site 8	P	0.1335	P	0.2309	P	0.8563	P	0.233	P	0.1025	P	0.0384
	T	2.0445	T	1.4986	T	0.1972	T	1.49	T	2.3263	T	3.5404

Table 3. T-test results for biological oxygen demand, including P-values and T-values. Degrees of freedom for all is 3. All samples dates (7/12/19, 7/19/19, 7/26/19, 8/5/19, 8/12/19, and 8/21/19) were compared against the pre-treatment values (7/2/19 sample date) for each site. Significance was determined using a Bonferoni correct P-value of P=0.01.

FIGURES

Figure 1. The invasive aquatic plant, yellow floating heart (*Nymphoides peltata*). Yellow floating heart was first detected in Lake Carl Blackwell, Stillwater, OK, in 2014. Image Source: Oklahoma Department of Environmental Quality.

Figure 2. Yellow floating heart on Cove D in Lake Carl Blackwell at near peak infestation coverage in September 2018.

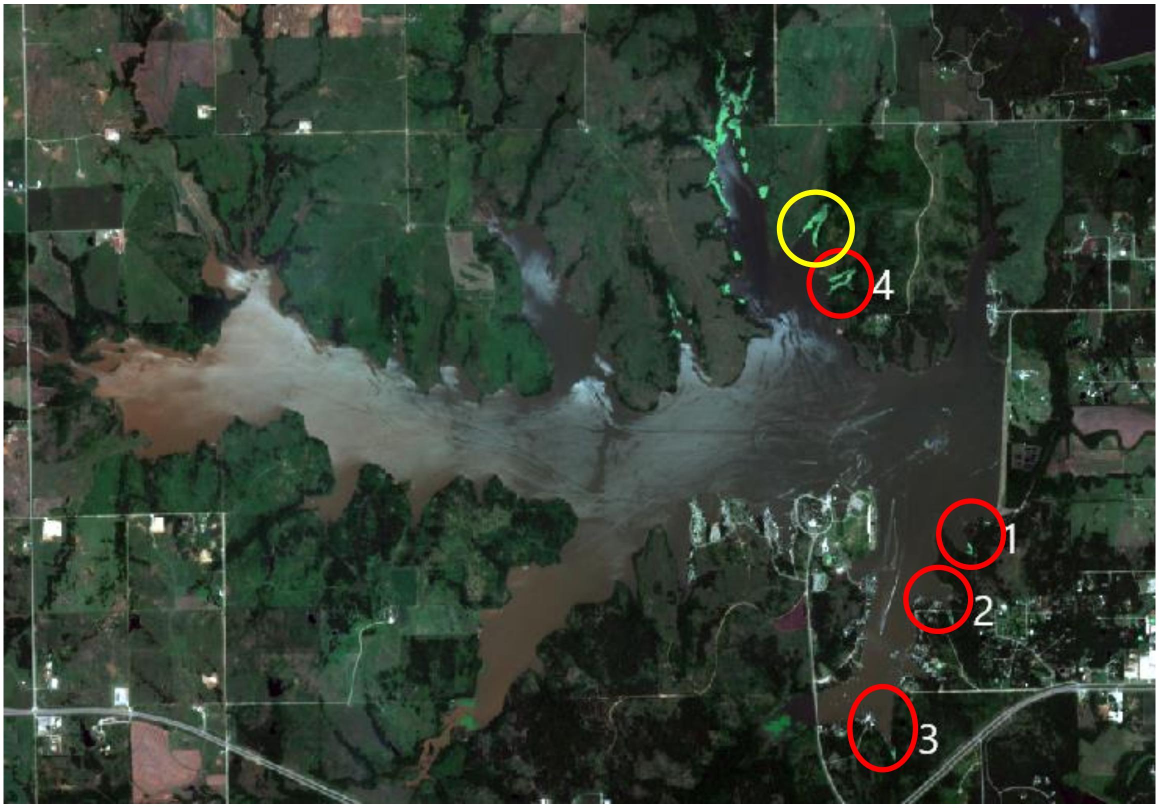


Figure 3. Satellite image from Sentinel-2 of Lake Carl Blackwell in Stillwater, OK taken on 6/29/2019 when yellow floating heart was at its peak coverage. The light green area at the margins of the large, north-eastern cove is yellow floating heart. Cove D is circled in yellow. The coves observed in the depth distribution section and Figure 8 are circled in red.

Figure 4. Cove D in Lake Carl Blackwell and the location of the seven sample sites. Bright green areas indicate yellow floating heart. Image does not show yellow floating heart at full extent of 2019 growing season.

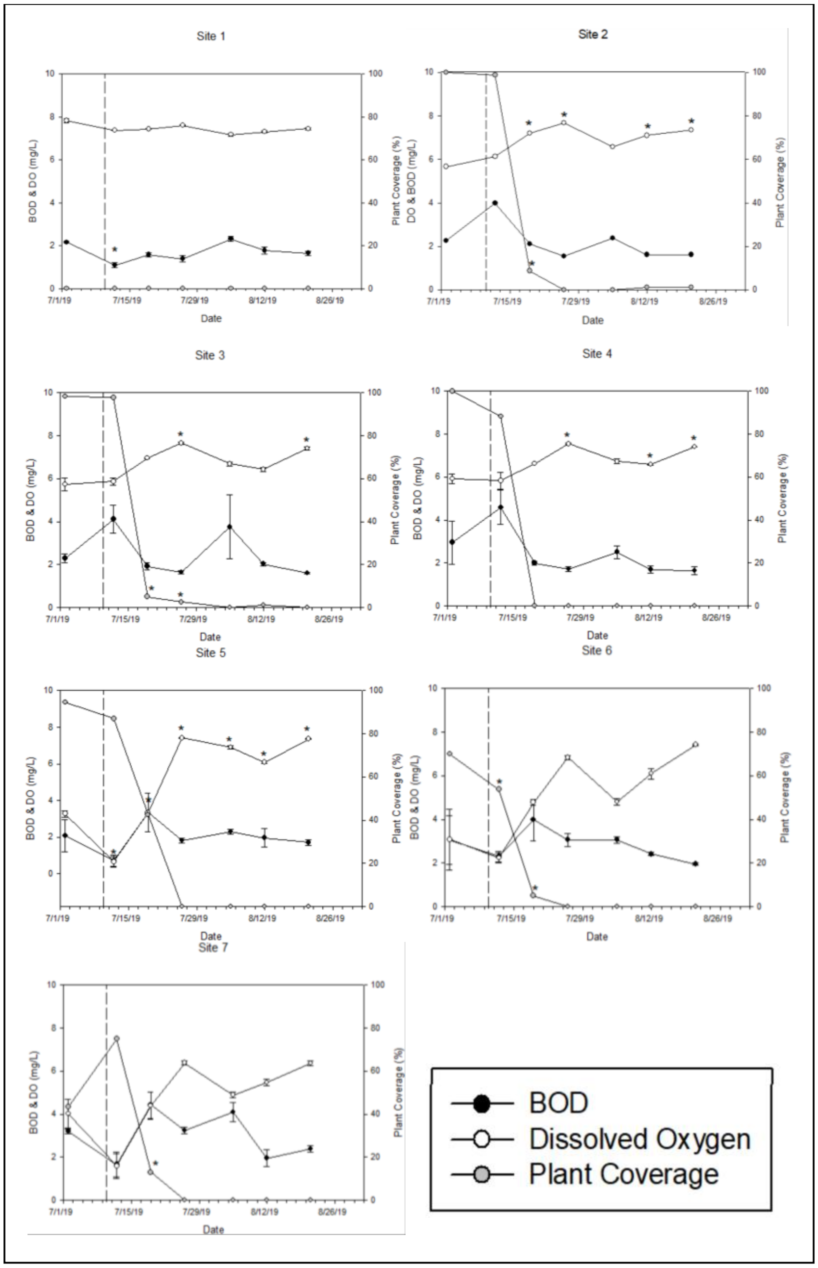


Figure 5. Biological oxygen demand (black points), dissolved oxygen (white points) and yellow floating heart plant coverage (gray points) at the seven sample locations in Lake Carl Blackwell. The vertical bar represents that date of chemical treatment. Significant differences between pre- and individual post-sample dates are represented by * from t-tests with a Bonferoni correct P-value of P=0.01.

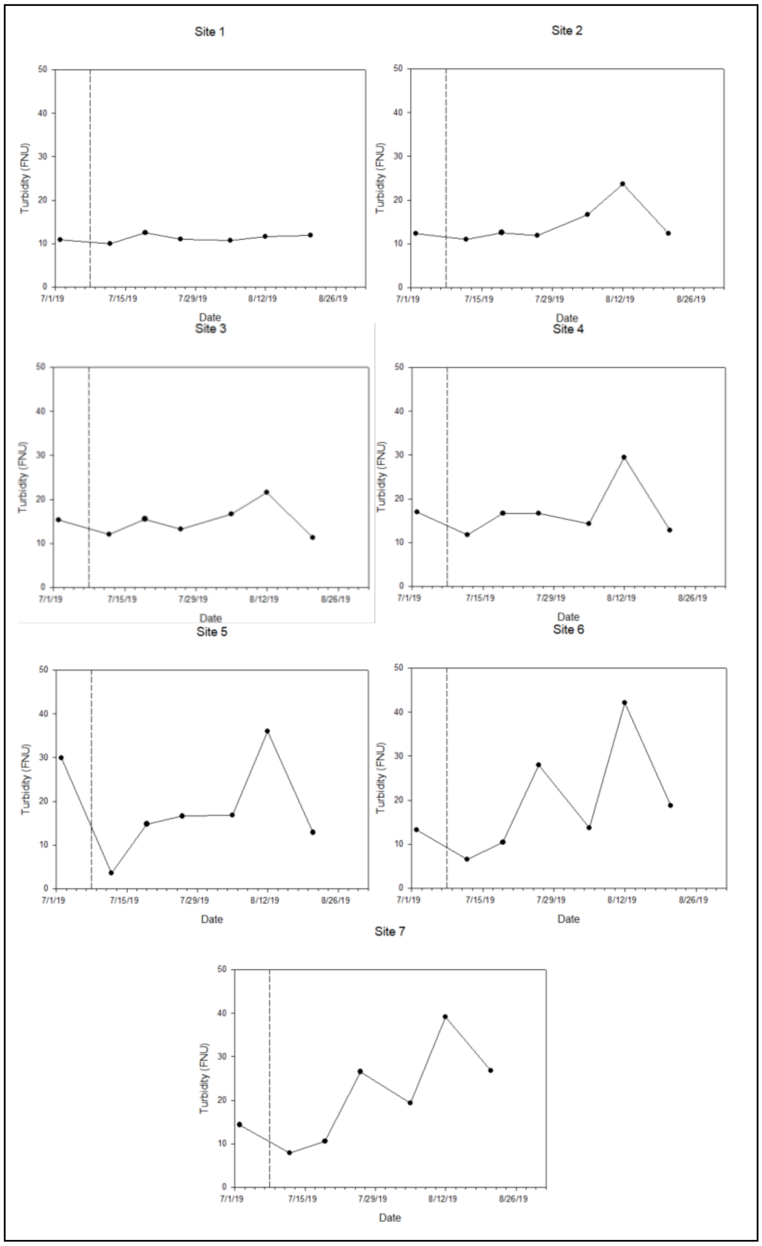


Figure 6. Turbidity concentrations at the seven sample locations on Lake Carl Blackwell. Vertical bar indicates the date of treatment.

July 12th, 2019 (2 days after treatment)

July 19th, 2019 (9 days after treatment)

July 26th, 2019 (16 days after treatment)

August 12th, 2019 (33 days after treatment)

Figure 7. Timeline images of yellow floating heart surface coverage on Lake Carl Blackwell's Cove D following Procellacor™ treatment. Images occur 2, 9, 16 and 33 days after treatment.

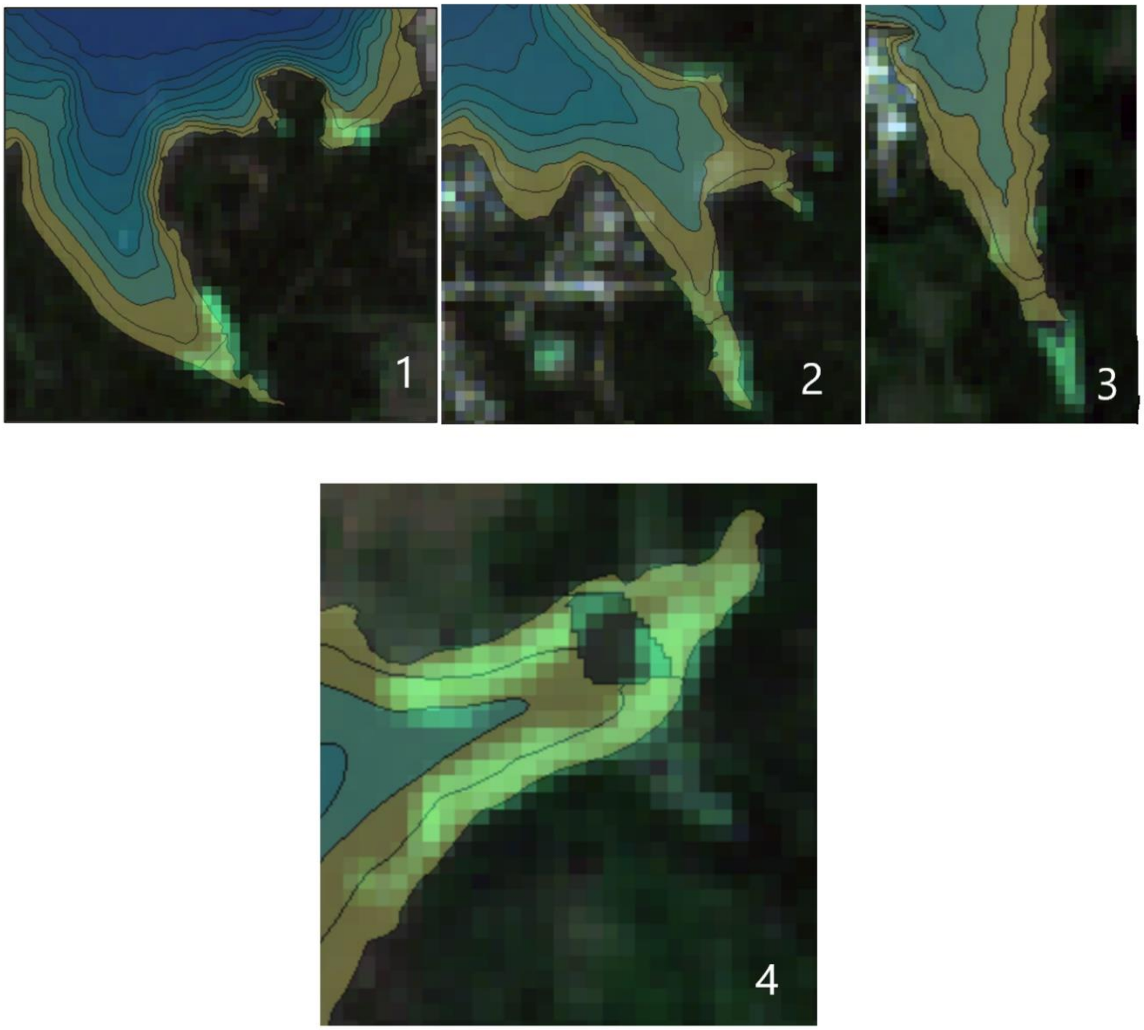


Figure 8. Yellow floating heart infestations on three southern coves (top images) and one northern cove (bottom image) in Lake Carl Blackwell. See Figure 3 for position of each site in the reservoir. Green pixels indicate yellow floating heart. Yellow depth contours indicate depth (0-1m, 1-2m, 2-3m) that yellow floating heart can grow.

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APPENDICES

Summary of Management Practices

Invasive aquatic plant management is a complex discipline that can be difficult to plan, expensive to operate, and unsuccessful if done incorrectly (Madsen, 2000). Management practices should be selected based on target species, non-target effects, project objectives, available funding, and stakeholder perspectives (Netherland et al., 2005). All aquatic plant management techniques have positive and negative attributes that should be considered on a site-specific basis. The selection of management techniques needs to be based on economic and technical constraints that are often dependent on the size of the area and/or the environment of the infested waterbody. Understanding and enacting the best management strategies can be helpful to ensure the most effective and efficient results. Multiple strategies must often be combined in order to obtain the desired results (Madsen, 2000).

Multiple strategies have been used to treat YFH at LCB over the past 3 years. These strategies included hand pulling of small infestations, benthic matting of areas that were close to the water intake structure, and multiple herbicide treatments (Glyphosate and Procellacor™). This review summarizes how each of these treatments were used in LCB including their advantages and disadvantages, estimated costs, and effectiveness. The purpose of this review is to use the knowledge gained from LCB to help guide future

YFH management efforts. A summary table of YFH treatment efforts at LCB is included in Table 1A.

Physical Removal:

Physical removal techniques include hand pulling, cutting, and harvesting of aquatic invasive plants (Madsen, 2000). This method can be relatively inexpensive for small infestations because it only requires labor costs. Physical removal is often most successful in smaller infestations (Madsen, 2000). Control efforts on larger infestations may not be logistically feasible and may require more mechanization such as aquatic weed harvesters. Disposal of plant material can also be difficult as it is generally more than 90% water and not suitable for feed (Madsen, 2000).

Hand pulling was used in LCB after chemical treatment to remove small stands of remaining vegetation and in larger areas near the water intake structure where chemical treatment was not initially allowed. I estimated this method would be most useful in small, isolated occurrences no larger than 0.1 acre and could range in cost between $330-$660 per 0.1 acre for paid labor associated with removal. Labor was estimated to take between 10-20 hours at $33 per/hour.

Physical removal of aquatic plants causes fragmentation of the plant material that can help to spread the plant throughout a reservoir or downstream to connected reservoirs. Yellow floating heart can reproduce by its seeds, stolons, rhizomes, and broken leaves with part of their stem remaining (Nault & Mikulyuk, 2009). While the physical pulling of YFH in LCB was effective at removing small stands of vegetation after herbicide treatment, it is not known if this contributed to further spread throughout the reservoir.

Benthic Matting:

Benthic barriers are mats that are installed on top of aquatic vegetation that are used to prevent or inhibit the growth of aquatic plants (Hofstra & Clayton, 2012). Benthic matting materials include sheets or screens of plastic, fiberglass, nylon, or other non-toxic materials. Permeable materials are suggested to allow gases produced during the degradation of plant material to escape. These mats kill the plants by blocking their access to light during the growing season and provide a physical barrier to growth by reducing the space available for expansion and by preventing plants from germinating (Kishbaugh, 1990). This method is most effective when used in small areas. Matting can be difficult to install and maintain and needs to be weighted down to be held in place. The cost of benthic barriers ranges because professional installation can be expensive, depending on the choice of material used (Kishbaugh, 1990), I estimated the cost for materials and installation for 0.1 acre of benthic matting would range between $4,070-7,025. The estimate is based on benthic matting material costs (Canadian Pond, 2020, Lake Bottom Blanket, 2020) and associated labor for installation. A problem with benthic matting is that aquatic plants can recolonize via fragmentation and suspended sediments on top of the benthic barriers or can grow around the edges and through permeable materials (Hofstra & Clayton, 2012).

Benthic mating was installed during the 2018 growing season in a small area in the south eastern part of LCB near the dam (Figure 1A). These materials were donated and personnel from the LCB, Oklahoma State University, and Oklahoma Department of Wildlife Conservation (ODWC) volunteered their time to help place the matting. The matting was placed in this area because it was located near the drinking water intake structure, which negated the use of some chemicals. This method was initially effective at killing YFH. However, plants began to regrow over the top of the benthic matting. Benthic matting can also be easily moved or damaged due to weather, either requiring maintenance or replacement if long term treatment is required. Flooding pushed the LCB benthic matting onto the shore at the beginning of the 2019 growing season so that it was no longer effective over a large area.

Herbicide:

Chemical control is a technique that is widely used by invasive aquatic plant managers (Madsen, 2000). Treatments can range in size from backpack spray applications for treating small clusters of plants to large-scale treatments using boats that target plants throughout an entire lake. Herbicide types differ between contact herbicides and systematic herbicides. Contact herbicides are often used for temporary treatment of sensitive free-floating plants and good coverage is essential for effective control (Netherland, 2014). These treatments are often initially effective but treating emergent plants with a contact herbicide can result in rapid recovery and regrowth from plant tissues that did not come into contact with the herbicide. Systemic herbicides are absorbed into the plant tissue and move through the plant's xylem or phloem. The herbicide moves throughout the plant tissue to affect all parts of the plant, including roots and rhizomes (Beets & Netherland, 2018). Systematic herbicides are usually preferred for controlling emergent plants because the herbicide will translocate within the plants and kill underground roots and rhizomes to reduce or eliminate regrowth (Netherland, 2014).

Glyphosate is a post-emergent, systemic, non-selective herbicide (WHO, 1994). Its aquatic version (Rodeo®) was used in LCB's treatment of YFH in the 2017 and 2018 growing seasons. I estimated the cost of treatment to be $185 per acre treated during each treatment. This estimate includes labor, boat and chemical costs. Over the growing season glyphosate was applied up to four times per infested cove but did not effectively stress or kill YFH (Angle, 2019). Aquatic glyphosate is applied directly to surface plant material, while the plant is photosynthetically active, and requires the herbicide to have sufficient contact time with plant tissue to be effective. This herbicide can take anywhere from 4 to 20 days to kill plant tissue beyond recovery. Rainfall, wind, waves, and currents can shorten glyphosate contact time with YFH leaves making it less effective (Getsinger et al., 2008; Henderson et al., 2010). Over time multiple unsuccessful applications per cove will become costly.

Procellacor™ is a postemergence, synthetic auxin herbicide that is selective in targeting susceptible grass, sedge, and broadleaf weeds. It targets plant reproduction and growth processes and is easily absorbed and translocated throughout the plant (Beets & Netherland, 2018; SePro, 2019). It has no drinking water use limitations and works best when it is applied under the surface (EPA, 2018). Procellacor™ was used on LCB during the 2019 growing season to treat for YFH. Cost of treatment was estimated to be $435 per acre each treatment. This estimate included labor, boat, and chemical costs. Treatment consisted of a single treatment per cove and reduced YFH from ~55 acres to less than 3 acres by the end up the sampling season.

Management Strategy	Description	Advantages	Disadvantages	Relative Cost	Quality of Results
Physical Removal	Includes hand pulling, cutting, or harvesting	- Environmentally friendly - Effective at removing small infestations - Can be used with other treatment methods to remove smaller stands	- Can aid in further YFH infestations - Requires lots of labor - May only be effective in small infestations -Infestation was too large in some areas to be feasible	- Estimated $330-660 per 0.1 acre[1]	-Effective on small infestations -Can ultimately aid in YFH spread -Short term

			- Does not prevent regrowth		
Benthic Barrier	Plants are covered with a growth inhibiting material	- Environmentally friendly - Effective in small areas	- Needs to be regularly inspected and maintained - Can interfere with native benthic organisms -Can be damaged by flooding	- Cost is variable based on material used and area covered - Estimated $4070-7025 per 0.1 acre[2]	-Temporarily effective on small areas -Over time YFH can regrow over and around matting
Glyphosate (Rodeo®)	Post-emergent, systemic, and non-selective herbicide	- Rapid dissipation	- Applied to surface of water - Requires multiple treatments per growing season -Can impact non-target organisms	- $185 per acre treated[3]	-Limited control of YFH even after multiple applications
Procellacor™	Post-emergence, synthetic auxin herbicide	- Efficient - Applied below the surface - Environmentally safe - No drinking water restrictions	- Requires certified applicator	- $435 per acre treated[4]	-Near complete control of YFH after one application

Table 1A. Summary of the management strategies that have been used to treat yellow floating heart on Lake Carl Blackwell since 2014.

[1] Cost for pulling estimated based on 10-20 hours of labor to remove YFH depending on plant density.
[2] Cost for benthic matting based on estimated benthic matting material and 40 hours of labor for placement.
3 Cost was calculated based on how much it cost to spray at maximum coverage. Includes cost of applicator, boat time and chemical. Cost associated with determining coverage prior to treating were not included.
4 Cost was calculated based on how much it cost to spray at maximum coverage. Includes cost of applicator, boat time and chemical. Cost associated with determining coverage prior to treating were not included.

Figure 1A. Benthic matting used to cover yellow floating heart in Lake Carl Blackwell, OK in the 2018 growing season. The benthic matting was placed on an infestation that was located near the water intake structure on the southeast part of the lake.

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