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ORIGINAL ARTICLE

Controlling *Lyngbya wollei* in three Alabama, USA reservoirs: summary of a long-term management program

Wesley T. Anderson[1] · Josh N. Yerby[1] · Jason Carlee[1] · West M. Bishop[2] · Ben E. Willis[2] · C. Todd Horton[3]

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Abstract

Large-scale *Lyngbya wollei* (Cyanobacteria, Oscillatoriales) infestations are increasing throughout the USA and globally and causing significant obstruction of water resource uses. Decision makers and stakeholders encountering this nuisance organism often seek management options. Many approaches to *L. wollei* management may be ineffective or not applicable to specific field sites. Chemical control with United States Environmental Protection Agency registered algaecides has shown to be effective, although the specific formulation, concentration, and application frequency can all govern efficacy. This study summarizes results from a long-term and adaptive management program on extensive *L. wollei* infestations in three central Alabama, USA reservoirs (Lay Lake, Jordan Lake and Lake Mitchell) managed by Alabama Power Company. Multiple treatment strategies including numerous algaecides, combinations and addition of surfactants were used in attempts to control the nuisance cyanobacterium and preserve multiple beneficial functions of the resource. Ultimately, operational shift toward one technology, a double-chelated copper algaecide with surfactants and emulsifiers (Captain® XTR) resulted in more efficient and economical control. There were significant ($P < 0.05$) decreases in historic *L. wollei* acres requiring treatment through time on each reservoir. Throughout this study period, a 51.4, 88.1 and 94.7% percent decrease in total nuisance acres treated was realized on Lay Lake, Jordan Lake and Lake Mitchell, respectively. The large-scale and long-term dataset presented herein, covering multiple candidate treatment programs, provides valuable information to guide management decisions on other water resources impacted by *L. wollei* infestations.

Keywords *Lyngbya wollei* · Cyanobacteria · Management · Algaecide · Copper

Introduction

Lyngbya wollei Farlow ex Gomont (Speziale and Dyck 1992 [syn *Microseira wollei*]) is a filamentous cyanobacterium that can achieve substantial biomass in freshwater resources and is proliferating in many areas throughout the USA (Bridgeman and Penamon 2010; Hudon et al. 2014). Growth forms include benthic, suspended and floating mats which impede critical water resource uses (e.g., power generation, wildlife habitat, recreation, property values) and can harbor pathogenic fecal bacteria (Vijayavel et al. 2013). *L. wollei* has been documented to produce numerous toxins that can negatively impact irrigated crops, livestock, wildlife and humans (Foss et al. 2012; Bhadha et al. 2014; Paerl et al. 2016). In large, multi-use reservoirs, disruption of critical water uses often requires implementation of management, although management initiatives must be in line with water use objectives. Multiple approaches (e.g., mechanical, biological, chemical, cultural) to *L. wollei* management are often considered. With dynamic nature (e.g., depth, location, access, terrain) of many of the typical infested sites, mechanical control is unlikely an effective option and requires dedicated personnel and maintenance (Calomeni et al. 2015). Biological control measures have not been shown to be a viable option for large-scale management of this species. Despite some anecdotal reports of elevated grass carp densities consuming *L. wollei*, it has been shown in numerous studies not to be preferred food source (Dyck 1994; Kasinak et al. 2015), and that carp can alter ecosystem

✉ West M. Bishop
westb@sepro.com

[1] Alabama Power Company, 744 Co Rd 87, Calera, AL 35040, USA

[2] SePRO Research and Technology Campus, 16013 Watson Seed Farm Rd., Whitakers, NC 27891, USA

[3] SePRO Corporation, Anderson, SC 29624, USA

functionality and negatively impact overall water quality (Dibble and Kovalenko 2009). Due to potential for efficacy and rapid ability to show results, United States Environmental Protection Agency (USEPA)-registered algaecides are a critical component of *L. wollei* management. Efficiency of algaecides and application programs can differ significantly (Bishop and Rodgers 2012; Bishop et al. 2018a). Selecting the most effective program is critical for achieving management objectives while decreasing costs, environmental load and operational inputs (Bishop and Rodgers 2011). Algaecide treatments can be implemented successfully for *L. wollei* infestations (Bishop et al. 2015), although successful management requires an increased understanding of exposure characteristics and temporal aspects of controlling large infestations.

The large mat structure formed by *L. wollei* is innately less responsive to many chemical control techniques (Lembi 2000). Thick mats restrict contact of applied algaecides to filaments in deeper mat layers. Visual reports suggest only the uppermost layer of the mat may show symptoms to algaecides, whereas lower layers appear uninjured and allow for continued growth. The large mucilaginous sheath (up to 60% of dry biomass), covering the multicell trichome, is comprised of homoglucan and cross-linked monosaccharides (Hoiczyk 1998). The sheath, in part, can provide resilience to chemical control measures (Tien et al. 2005) as has allowed growth in environments with elevated contaminants (Reynolds 2007). Even with effective treatment programs that result in non-viable *L. wollei*, the cellular structure often remains intact and not easily degraded (i.e., dead *L. wollei* possesses a similar biomass to living). It often takes months or years to discern biomass changes of *L. wollei* mats in field management scenarios due to heterogeneity, thickness and mobility potential. Tien et al. (2005) found that dead cells can sorb copper and may interfere with effectiveness of subsequent algaecide applications. Multiple treatments annually and long-term assessments allow the ability to distinguish results of management programs through time. This incorporates both the progression of non-viable material degradation along with contained control of new biomass, assuming the program is effective. Additionally, potential increased biomass from growth of viable biomass may be observed with ineffective management programs. The viability of the biomass can be used to assess the efficacy of short-term programs (Bishop et al. 2015). Although biomass alone often requires significant time to manifest as a response parameter, it is important to assess as dead biomass can impede utilization of water resources similar to live biomass.

In accordance with the critical burden concept, a specific amount of a USEPA-approved algaecide is predicted to only control a specific biomass of *L. wollei* (Bishop and Rodgers 2012; Bishop et al. 2018a). With dense infestations, a single application of any current registered algaecide at the maximum label rate is unlikely to achieve control of the entire *L. wollei* biomass; therefore, the presence of viable biomass will persist. A regimented control program to stepwise reduce biomass through time is often required. Significant differences in algaecide formulations, including those with similar listed active ingredients, have been documented (Bishop et al. 2018a). Chelated copper-based algaecides are common components of *L. wollei* management programs and are often combined with surfactants to aid penetration (Duke 2007; Bishop et al. 2015; Calomeni et al. 2015). The chelation is designed to improve stability of the copper ion in solution and alter charge properties of resulting copper complexes to passively penetrate cell membranes (Stauber and Florence 1987; Straus and Tucker 1993; Mastin and Rodgers 2000). Analyzing results of long-term management programs allows comparison of algaecide formulation efficiency at attaining control and achieving management objectives toward selecting an efficacious product for large-scale management.

The advent of large-scale *L. wollei* infestations in Alabama Power Company managed reservoirs (i.e., Lay Lake, Jordan Lake, Lake Mitchell) significantly threatened the ecological function, economic value and overall utilization of these systems. Critical functions of these systems include recreational activities (e.g., fishing, swimming, boating), economic impact (property values, aesthetics, tourism), anthropogenic uses (potable water source, industrial, irrigation) as well as wildlife habitat (including endangered species). Regimented algaecide applications, often > 5 applications per year, have been used to target infested areas of these systems for over two decades (Iwinski et al. 2016). Multiple algaecide treatment programs have been researched and utilized in Lay Lake, Jordan Lake and Lake Mitchell with the goal of decreasing *L. wollei* biomass to preserve management objectives (Duke 2007; Tedrow 2007; Bishop et al. 2015; Calomeni et al. 2015). The overall goal of this research was to summarize the primary treatment programs utilized in Alabama Power Company reservoirs as well as resultant effectiveness through time. As *L. wollei* infestations are common throughout the southeastern United States (Speziale and Dyck 1992; Regan et al. 2017) and continue to spread, especially through the Laurentian Great Lakes basin (Bridgeman and Penamon 2010; Vijayavel et al. 2013), long-term datasets covering multiple candidate treatment programs can be extremely valuable to guide management decisions in different sites.

Specific objectives of this study were to (1) summarize approaches to management of *L. wollei* in three central Alabama reservoirs (Lay Lake, Jordan Lake and Lake Mitchell); (2) compare the effectiveness of different algaecide treatment programs for controlling *L. wollei* based on the change in acres treated through time; (3) assess parameters leading to alterations in management programs.

Methods

Site description

Three man-made reservoirs impounded along the Coosa River in central Alabama, USA, that received historic algaecide treatments for widespread *L. wollei* infestations were selected for this study (Fig. 1). Lay Lake, 12,108 surface acres (4900 ha), was built in 1914 and is located within St. Clair, Talladega, Shelby, Coosa and Chilton Counties; Jordan Lake, 6800 surface acres (2752 ha), built in 1928 is in Elmore County; and Lake Mitchell, 5859 surface acres (2371 ha), built in 1922 is located in Chilton and Coosa Counties. Infestations of *L. wollei* were located throughout all reservoirs. Mats often formed on the bottom of the reservoir and proceeded to move through the water column and form aggregated surface mat accumulations later in the year. Infestations were typically found in localized cove and/or shoreline areas of these dendritic reservoirs and growing to depths of up to 5 m. Treatment sites were selected based on notable mats of *L. wollei* present in the majority of the treatment area. Treatment areas ranged from 0.25 to 16.5 acres in size with a mean of 1.35 surface acres (0.55 ha).

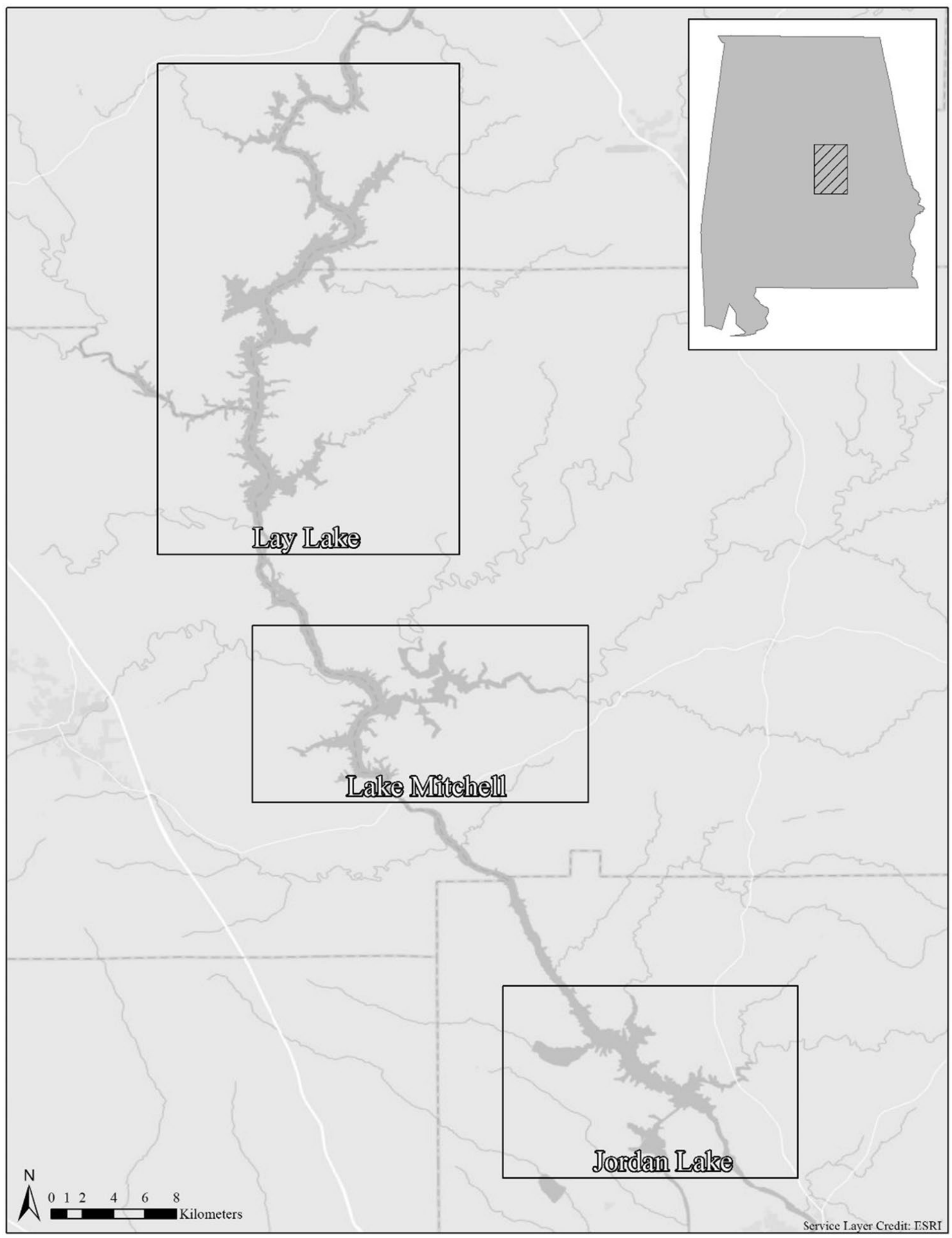

Fig. 1 Map and location of the three central Alabama reservoirs evaluated in this study

Data acquisition

Detailed records of algaecide and application costs were kept annually regarding *L. wollei* management. Records of product costs, contract application costs and internal application costs (if applicable) were maintained by the Environmental Affairs Department of Alabama Power Company. Annual inputs since 2013 for *L. wollei* management were compiled to use in this study assessment, although regular applications have occurred for over 20 years.

Algaecide treatment programs

Numerous USEPA-registered algaecides, approved for use in lakes and reservoirs, were primarily used to control *L. wollei* infestations in the three reservoirs. Product combinations, sequential applications and addition of approved aquatic surfactants were a component of many management programs. A list and description of the algaecides utilized in treatment programs over the last 6 years are presented in Table 1. Application of the algaecides was conducted by state-certified aquatic applicators and followed all label, shipping and regulatory requirements. Most applications were contracted with the professionals at Aqua Services, Inc. Treatment programs primarily consisted of five applications per year to each treated site. Note that in some years additional treatment sites were added later in the year and thus received less than five annual treatments. A GPS-guided application system was used to ensure good coverage and targeted algaecide amounts throughout the specific treatment area. With liquid applications, appropriate amounts of algaecide were placed in a 200-gallon tank and applied via subsurface injection to target benthic mats. A patented HD AQUA® system designed by Aqua Services, Inc. was used to inject a course spray of the product to the bottom contour of the

Table 1 Comparison of physical and chemical properties of the primary algaecide formulations tested in attempts to control *L. wollei*

	Captain® XTR[a,b]	Cutrine® Ultra[c]	Algimycin®-PWF[d,e]	Phycomycin®-SCP[f]	Green Clean® Liquid 2.0[g,h]	Hydrothol® 191[i,j]
Manufacturer	SePRO Corporation	Applied Biochemists	Applied Biochemists	Applied Biochemists	BioSafe Systems, LLC	UPL NA, Inc.
Identification (EPA Reg. No.)	67690-9	8959-53	7364-9-8959	68660-9-8959	70299-12	70506-175
Active Ingredient (formulation)	Copper–ethanolamine complexes (SP9000 surfactants)	Copper–ethanolamine complexes (D-limonene)	Chelates of copper citrate and gluconate	Sodium carbonate peroxyhydrate	Hydrogen dioxide/ Peroxyacetic acid	Mono(*N*,*N*-dimethylalkylamine) salt of endothall
% Active Ingredient complex	28.2	27.8	25.4	85	27.1/2	53
Chelator amount	Triethanolamine complex—14.9% Monoethanolamine complex—13.3%	Triethanolamine—20–30% Ethanolamine—18–28%	Chelates of copper gluconate 12.5% Chelates of copper citrate 12.9%	NA	NA	NA
Appearance	Blue viscous liquid	Blue viscous liquid	Blue liquid	White, granular solid	Clear, colorless liquid	Dark yellow light brown liquid
Water solubility	Miscible	Miscible	Miscible	140 g/L (20C)	Soluble	Soluble
pH (SU)	10–10.5	10.2–10.3	1.5–2.5	10.4–10.6 (3% solution)	0.96	Not listed
Specific Gravity (g/cm^3)	1.2	~1.2	~1.2	0.9–1.2	1.1	1.044 (25C)

[a]SePRO Corporation. 2014. Captain XTR Algaecide Product Label. SePRO Corporation Carmel, IN 46032

[b]SePRO Corporation. 2018. Captain XTR Algaecide Safety Data Sheet. SePRO Corporation Carmel, IN 46032

[c]Applied Biochemists. 2015. Cutrine Ultra Algaecide Safety Data Sheet. Applied Biochemists Inc. Germantown, WI 53022

[d]Applied Biochemists. 2010. Algimycin PWF Algaecide Safety Data Sheet. Applied Biochemists Inc. Germantown, WI 53022

[e]Applied Biochemists. 2014. Algimycin PWF Algaecide label. Applied Biochemists Inc. Germantown, WI 53022

[f]Applied Biochemists. 2015. Phycomycin Algaecide and Oxidizer Safety Data Sheet. Applied Biochemists Inc. Germantown, WI 53022

[g]BioSafe Systems LLC. Green Clean Liquid 2.0 Safety Data Sheet. East Hartford, CT 06108

[h]BioSafe Systems LLC. Green Clean Liquid 2.0 Product label. East Hartford, CT 06108

[i]UPL. 2017. Hydrothol 191 Aquatic Algaecide and Herbicide Product Label. UPL NA, Inc. King of Prussia, PA 19406

[j]UPL. 2018. Hydrothol 191 Aquatic Algaecide and Herbicide Safety Data Sheet. UPL NA, Inc. King of Prussia, PA 19406

treatment site to promote increased algaecide interaction with benthic mats. This system automatically accounted for changes in depth profiles and hydraulically raised and lowered the spray boom to maintain a consistent injection of the product near the bottom (~ 0.3 m) of the site. In shallow water (< 0.6 m), where it was difficult to get good contact with injection applications, surface spray applications were additionally conducted starting in 2013. Annual treatments typically started in April after the water temperatures increased (~ 18C), although in one winter (December 2013–February 2014) additional earlier season treatments were conducted to more dormant *L. wollei* to evaluate whether results improved. An overview of each treatment program is outlined below, and more details are summarized in Table 2.

Program 1

Phycomycin®-SCP was applied ~ 24 h preceding Algimycin®-PWF combined with the surfactant Cide-Kick® II. Products had to be applied on separate days to avoid large pH swings in a short time period. Phycomycin SCP was injected into the water column to promote interaction with benthic mats. The follow-up application of Algimycin PWF was combined with Cide-Kick II in the spray tank setup described above.

Program 2

Green Clean® Liquid 2.0 and Hydrothol® 191 were combined in a single tank mix with water to target *L. wollei* mats. Anecdotal reports of additive or synergistic impacts warranted evaluation of this approach.

Program 3

Cutrine® Ultra was used alone as well as with an additional surfactant, Cygnet® Plus. These were pooled together under this single program designation for analysis purposes. The Cutrine formulations (Plus and Ultra) were also the primary products that had been historically used prior to 2008.

Program 4

Phycomycin®-SCP was applied ~ 24 h preceding Captain® XTR. This sequence was conducted to compare with Captain XTR alone to evaluate whether the added peroxide assisted with mat destruction or algaecide penetration to increase efficacy.

Program 5

Captain® XTR alone was used in this program. Algaecide was diluted in the spray tank or applied as concentrate. The high density of this product in the concentrate spray solution may have allowed increased interaction on benthic mats.

Table 2 Description of *L. wollei* treatment programs used on the three Alabama reservoirs from 2013 to 2018

Program designation	Program products	Product applied per treated surface acre	Max amount of product applied per year (all reservoirs)	Relative chemical and application costs[a]	Notes
1	Phycomycin SCP => Algimycin PWF + Cide-Kick II	45–105 lb => 11–26 gall	44,207 lb => 11,079 gall	High	Two separate applications pH alterations Ecotoxicity Mat displacement Oxidizer PPE
2	Hydrothol 191 + Green clean liquid (granular in 2014)	0.49–1.8 gall + 1.33–5 gall	991 gall + 3331 gall	High	Two separate products Ecotoxicity Oxidizer PPE
3	Cutrine ultra ± Cygnet plus	19–22 gall	128 gall + 8.5 gall	Moderate	Historic use Ecotoxicity PPE
4	Phycomycin SCP => Captain XTR	95–100 lb => 14–15 gall	22,487 lbs => 3373 gall	High	Two separate applications Mat displacement Oxidizer PPE
5	Captain XTR alone	6–17.5 gall	7727 gall	Moderate	Single product PPE

[a]Additional information available upon request

Data analysis

All treatments sites were surveyed periodically throughout treatments, especially at the start and end of treatment programs. Visual assessments, including benthic rake tosses, were used to assess whether prior treatment sites required more treatments the same year or subsequent years. In later years, ciBioBase® imagery from a Lowrance™ depth finders was also utilized to visualize the presence of benthic mats. The decision to add/maintain a treatment site for a given year was based on the presence of a notable (~200 g ww/m^2) biomass of *L. wollei* in collected samples from that plot. Some plots were added back into treatment programs mid-season if notable increase in *L. wollei* was found post-initial sampling. Percent decreases in acres treated each year on each reservoir were calculated by dividing acres treated in a given year by initial acres at the start of this summary (2013). Regression analyses were conducted on percent decrease in acres treated through time on each reservoir to assess whether significant ($\alpha = 0.05$) correlations existed. Since new acres, not previously treated, were added on Lay Lake in 2017/2018, these were excluded from this analysis. All analyses and graphs were performed using Microsoft Excel (Microsoft 2010).

Results and discussion

Shift in algaecide treatment programs

Algaecide treatment programs prior to this study period primarily utilized Cutrine Plus and Cutrine Ultra. Marginal results, which at most produced growth suppression, were seen from these treatment programs with similar acres requiring applications annually. Numerous university-based laboratory bioassays were conducted to compare efficacy of different treatment programs (Duke 2007; Tedrow 2007). The program developed through this research (*Program 1* outlined above) was also used for many years, starting in 2008, with variable results. In 2013, this program was implemented on ~50% of the targeted *L. wollei* treatment acreage. Most other acres treated in 2013 year utilized *Program 2*, which included a combination of two products in a single tank mix and an active ingredient not previously applied (Figs. 2, 3, 4). Additionally, in attempts to continue to optimize treatment programs, Alabama Power Company also evaluated a newly registered product in Lay Lake (*Program 5*; Captain XTR) which later received a patent on the unique formulation design (Ullah et al. 2015). Starting midway through the 2013 application season, *Program 5* was implemented on a limited number of acres.

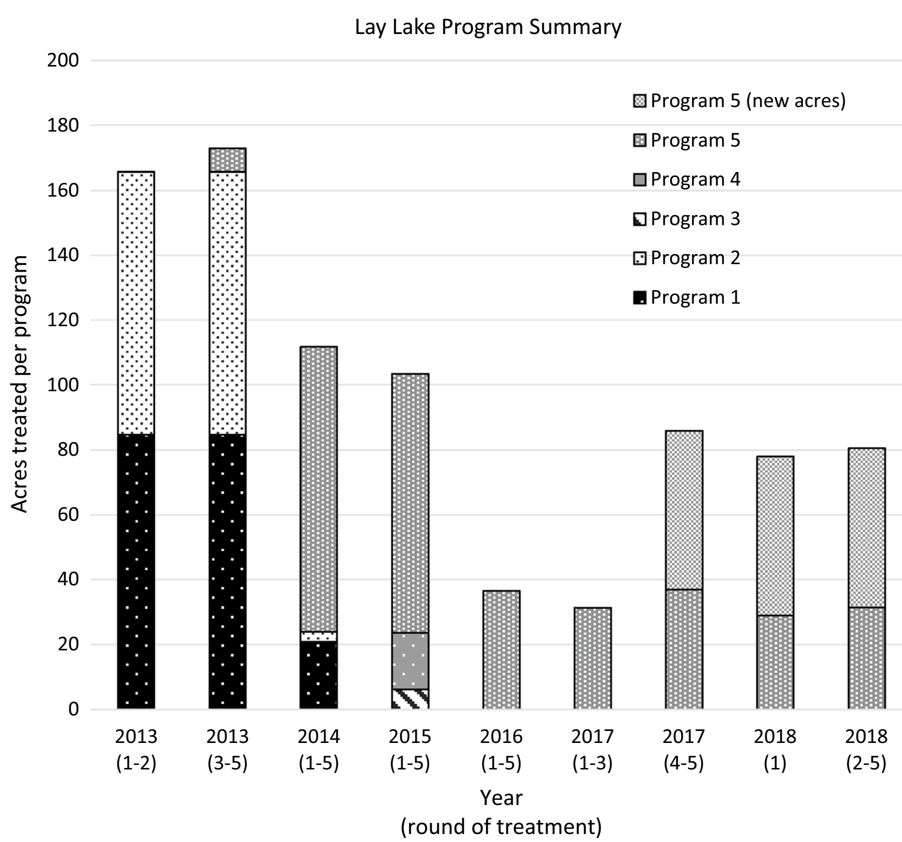

Fig. 2 Surface acres of nuisance *L. wollei* infestations treated with each algaecide treatment program in Lay Lake through time

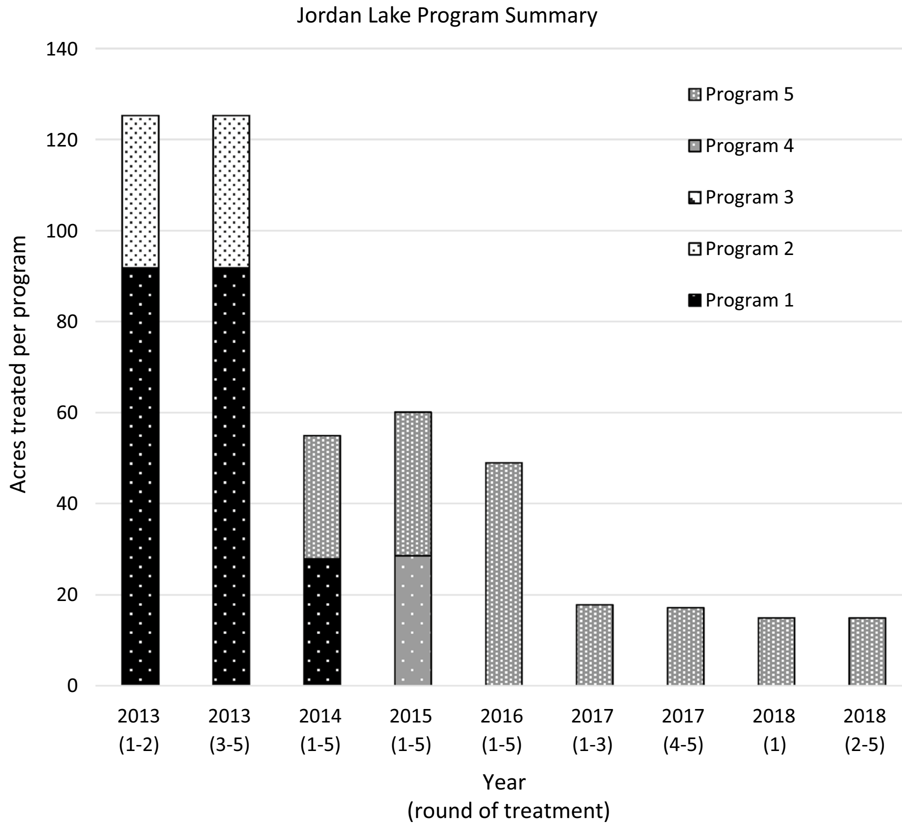

Fig. 3 Surface acres of nuisance *L. wollei* infestations treated with each algaecide treatment program in Jordan Lake through time

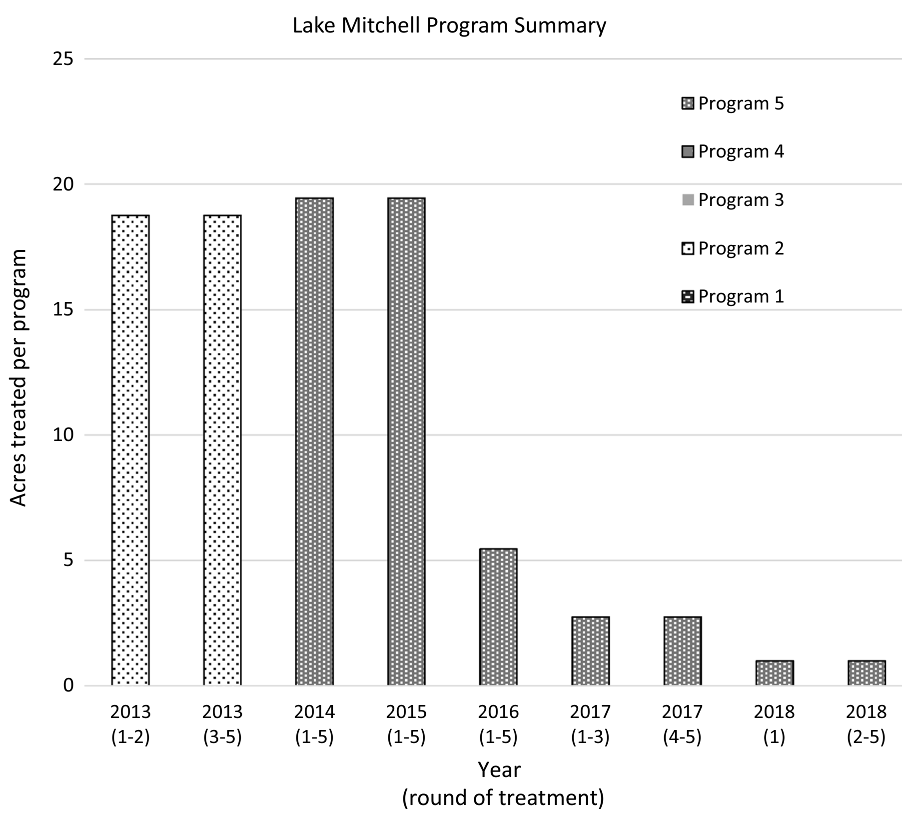

Fig. 4 Surface acres of nuisance *L. wollei* infestations treated with each algaecide treatment program in Lake Mitchell through time

The tests with *Program 5* from 2013 yielded positive results, and the majority of the *L. wollei* treatment sites in 2014 were shifted to this treatment method. Costs for this product compared with the combination of products (*Program 2*) that it replaced were essentially equal. The applicators only had to transport and handle one product vs two, which resulted in improved application efficiency. This product also had less personal protective equipment (PPE) requirements than products used in the combination treatment (*Program 2*). In 2014, 26% of the treatment acreage remained on *Program 1*. The remaining 74% was treated using *Program 5*. One smaller scale plot remained with an altered version of *Program 2*, where the Green Clean Liquid was replaced with a larger granular formulation to target benthic mats. However, the difficulty of application and PPE requirements were deemed to be too great to integrate into future treatments. Alabama Power Company staff also continued research efforts with university students involving different algaecide treatments, and their effects on *L. wollei* sampled from Lay Lake. None of those additional treatment options tested by the university were effective enough to justify the increased cost associated with them and therefore not utilized in future programs.

Based on the promising results documented in sites managed with *Program 5* from 2013 to 2014, all operational treatment sites were shifted to include Captain XTR, either alone (*Program 5*) or as a sequential treatment following Phycomycin SCP (*Program 4*). Additionally, in a continued effort to further explore and compare control options, Alabama Power Company staff assisted an algaecide manufacturer, in concert with a university, in evaluating test plots on Lay Lake using Cutrine® Ultra alone or tank mixed with an additional surfactant (*Program 3*). Based on the efficacy results attained by the university, these two methods were not effective enough to warrant further testing.

The end of season surveys from 2015 demonstrated the combination treatment (*Program 4*) was no more effective than the Captain XTR product alone (*Program 5*). Eliminating Phycomycin SCP from the treatment prescription also significantly reduced overall program costs by reducing product and labor expenses. Applicator efficiency also increased along with a decrease in logistics and risks associated with these two products versus one product. All reservoirs were therefore shifted to Captain® XTR alone (*Program 5*) by 2016. The ciBioBase mapping program was fully utilized in 2016, and average depths and total volume throughout treatment sites were better able to be estimated. This allowed optimization of the treatment strategy to achieve necessary exposures to attain control (Bishop et al. 2015).

Treatment site surveys in Spring 2017 demonstrated continued positive results from *Program 5*. Numerous sites with little or no growth were removed from the treatment list and placed on a monitor list. The remaining sites continued five annual applications using *Program 5*. Only two small sites (total 2.75 A) remained on Lake Mitchell, and the decision was made to treat those with internal staff. Two remote sites (0.65 A total) on Lake Jordan were also treated in-house. After the third round of treatments in mid-summer, nine old sites showed re-growth on Lay Lake and were placed back on the contractors treatment list. Additionally, 17 new sites totaling 49 acres not previously treated were added to treatment sites. Each site was mapped with ciBioBase to determine average depths for herbicide rate calculations.

In 2018, consistent positive results were documented with *Program 5* and this was again selected for use in all treatment sites. Site surveys on Mitchell Lake indicated little/no growth and greatly decreased biomass of *L. wollei*, and the decision was made to only monitor these sites through 2018. The 2018 growing season was the warmest over the study period. Treatment acreage on Lay and Jordan reservoir was similar between 2018 and 2017, and one new site was added on Lay Lake after the first round of treatment. Treatment sites maintained the similar levels of biomass but never exhibited a significant reduction through five rounds. The high re-growth rates prior to subsequent treatments and high existing biomass were thought as responsible for this. Numerous homeowner requests were received for *L. wollei* treatments that were not included in the initial program acres due to the high growth in these untreated areas throughout 2018. These new requests were given one late season (August) treatment of Captain XTR by Alabama Power Company staff, and those sites will be surveyed to determine the necessity of adding them to the 2019 treatment program.

Decrease in treated acres through time

From 2013 to 2018, drastic decreases in total treated acres were measured for each reservoir (Fig. 5). The lowest level of treatment acres documented in Lay Lake (31.42) occurred at the beginning of 2017 and was an 81% decrease compared with initial acres in 2013. This was after 3 years of treatment primarily with *Program 5*. However, primarily due to addition of 17 new sites (49 acres) with nuisance *L. wollei* growth that had not previously been treated, treatment acres increased in later 2017 and 2018. Excluding these new acres, an 81% decrease in treated acres would have consistently been realized in Lay Lake in 2018. Including these acres, total treated acres were still down 51.4% in Lay Lake at the study completion compared with original acres targeted. In 2013, at the beginning of the study, Jordan lake had 125.26 surface acres in a *L. wollei* treatment program. After two seasons (2015–2016) with Captain XTR as a component of all treatment programs, Jordan Lake had an 86.3% decrease in acres requiring treatment in 2017. There was a continued decrease in acres treated in 2018 (14.93 total), representing

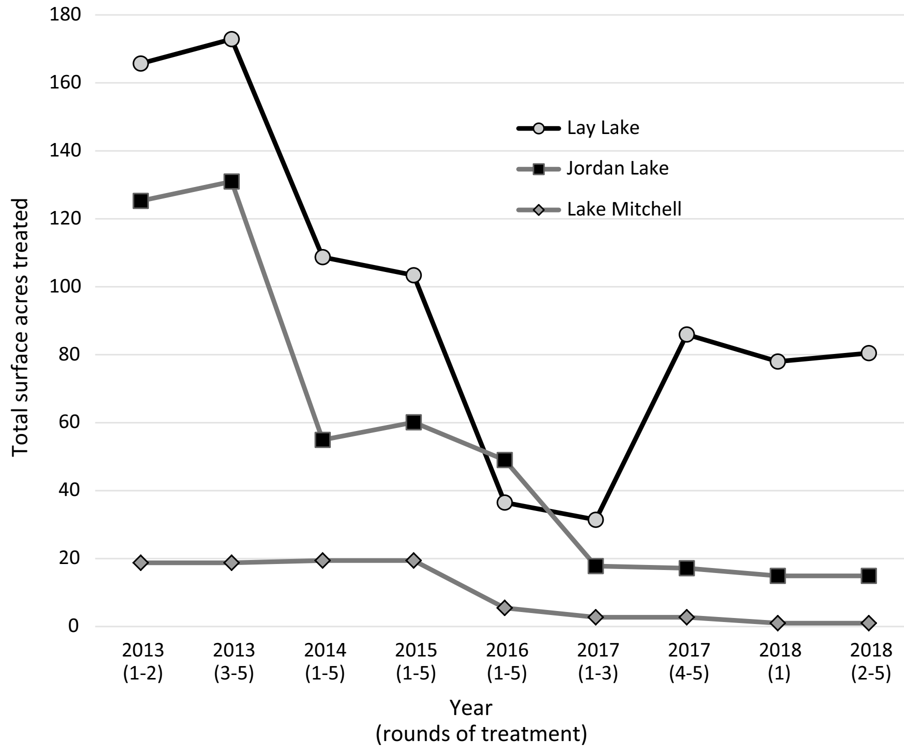

Fig. 5 Total surface acres treated for nuisance *L. wollei* infestations in three Alabama reservoirs through time

88.1% fewer acres than in 2013. On Lake Mitchell, after 2 years of treatment with *Program 5* (2014–2015) treatment acres decreased by 70.9% to 5.46 total acres in 2016. Treated acres continued to decrease in 2017 to 2.75 total acres representing an 85.4% decrease. In 2018, only one acre required treatment, a 94.7% decrease from the starting acreage treated in 2013.

In general, there was a positive trend comparing percent of acres receiving Captain XTR treatment with the decrease in number of acres requiring treatment (Fig. 6). A 1–2 year lag before seeing the acreage decrease was typically observed as it often takes time for thick infestations to be fully controlled and degrade. Linear regression analyses resulted in significant decreases ($\alpha = 0.05$) in continuing acres treated throughout this study period on all reservoirs. Lay Lake $R^2 = 0.89$ and $P = 0.005$; Jordan Lake $R^2 = 0.72$ and $P = 0.033$; and Lake Mitchell $R^2 = 0.85$ and $P = 0.009$. This decrease in acres requiring treatment also closely corresponds to decreases in both algaecide costs and application costs. By aggressively managing to attain

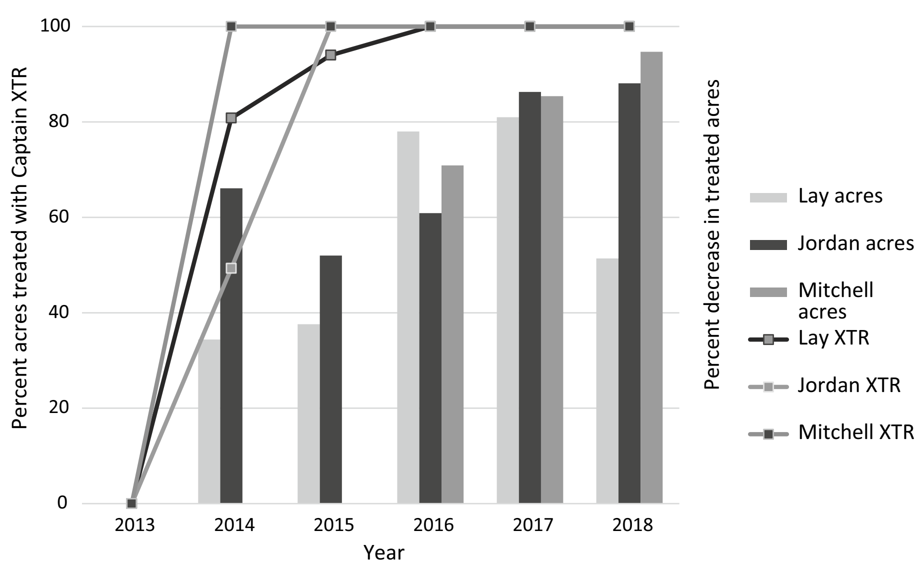

Fig. 6 Percent acres treated with Captain XTR (primary *y*-axis; lines) compared with percent decrease in total treated acres of *L. wollei* (secondary *y*-axis; bars) in three Alabama reservoirs through time

significant reduction in *L. wollei* biomass to levels that do not require treatment, the long-term program costs have greatly decreased as well as improved program efficiency.

Risk assessment of programs

Significant research efforts were implemented to ensure the selected treatment programs would continue to support the diverse functions of the reservoir. These were also considered in concert with the negative impacts *L. wollei* infestations had on all use objectives for the reservoir, including aquatic habitat quality and maintenance of water uses by the public. Except for one cove that received a recent treatment, no difference in sediment total copper concentrations was measured in treated and untreated coves in Lay Lake. In situ benthic invertebrate abundance was also not significantly different between treated and untreated coves (Iwinski et al. 2016). Additionally, all treated coves tested have similar or increased survival of *Chironomus dilutus* and *Hyalella azteca* in sediment toxicity tests with sampled sediment at different points in time (Calomeni et al. 2015; Iwinski et al. 2016). Short-term laboratory toxicity studies on sentinel aquatic organisms showed that components of *Program 1* may have some impact to larval fish or invertebrates (Johnson et al. 2008; Calomeni et al. 2015).

Program 5 showed increased effectiveness on *L. wollei* (and other algae) compared with other copper-based algaecides tested, including some of those previously used in the study reservoirs (Bishop et al. 2018a). Field research with *Program 5* in 2013 also supported its effectiveness in applied management programs in these reservoirs (Bishop et al. 2015). Rapid copper sorption has been documented following Captain XTR exposures, including with short contact times (Bishop et al. 2017; Willis et al. 2018). The formulation also results in increased internalized copper into *L. wollei* biomass which is significantly correlated with control (Bishop et al. 2018a) and less likely to desorb back into the water (Bishop et al. 2018b). The ethanolamine-chelated copper in the formulation is innately less toxic to nontarget organisms, and the rapid/sustained sorption further decreases copper availability to water-column species (Wagner et al. 2017; Bishop et al. 2018c). There is no water use restrictions following application of Captain XTR (e.g., irrigation, swimming/other recreation, livestock watering, potable source water), and therefore compatible with the diverse use objectives of the reservoirs (SePRO 2014).

Range expansions of *L. wollei*, especially large-scale infestations (Bridgeman and Penamon 2010), coupled with the high potential for ecological impacts (O'neil et al. 2012; Burkholder et al. 2018), human health and economic ramifications (Carmichael and Boyer 2016; Hudon et al. 2014) justify need for management. Risks are innately present with any applied management program, although these should be considered in context of risks of no management (Bishop 2016). Often there is less diversity of aquatic organisms in *L. wollei* infestations compared with native plants as well as less availability of invertebrates to support the food chain due to the habitat alteration (Tourville Poirier et al. 2010; Hudon et al. 2012). Some of the organisms documented in these mats are also not desirable, such as leeches (Annelida, Hirudinea). *L. wollei* infestations can be inversely related to establishment of native plants and more beneficial algae (Hudon et al. 2014 and references therein). Effective management of *L. wollei* can allow for an increase in beneficial habitat for native organisms (Tourville Poirier et al. 2010).

Management implications

Management programs using herbicides for invasive aquatic macrophytes have been documented in the literature and outline the intensity of management required to attain significant control (Getsinger et al. 1997; Madsen et al. 2002). However, little data exist on long-term algal management programs using USEPA-registered algaecides. *L. wollei* is a very resilient and adaptable cyanobacterium that is extremely difficult to control. Alabama Power Company has spent a significant amount of time focused on research into *L. wollei* control in these reservoirs and identifying most effective, economically feasible and ecologically appropriate solution for management (Duke 2007; Tedrow 2007; Bishop et al. 2015; Calomeni et al. 2015). Evaluating multiple treatment concepts, novel products/technologies and unique use patterns has helped establish an effective Alabama Power Company treatment program. Large-scale infestations are increasing across the country, especially in the southern, midwest and northeast USA (Hudon et al. 2014; Regan et al. 2017). Information documented from this applied management program can provide guidance to decision makers facing similar questions on overall management approach as well as associated time/cost and effort needed to effectively control *L. wollei* infestations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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