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Monoecious hydrilla tuber dynamics following various management regimes on four North Carolina reservoirs

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ABSTRACT

Hydrilla [*Hydrilla verticillata* (L.f.) Royle] is a federally listed noxious weed that has quickly spread through much of the United States. Long-term hydrilla control is complicated by persistent subterranean turions (tubers) that have been shown to remain viable for at least 6 yr. Tuber bank elimination is essential for long-term management or eradication efforts. Research was conducted on four North Carolina reservoirs to evaluate monoecious hydrilla tuber dynamics and to determine the effects of specific management techniques on monoecious hydrilla tuber densities over time. Lake Gaston, Lake Tillery, Shearon Harris Lake, and the Tar River Reservoir were sampled for up to 7 yr. Management practices and their effects on tuber density were assessed on each lake. Fluridone treatment sites were assessed on Lakes Tillery and Gaston, whereas a combination of fluridone application, drought-induced summer drawdown, and late-stage triploid grass carp stocking was assessed on the Tar River Reservoir. Sites on Lake Gaston and Shearon Harris Reservoir with no active management were also monitored. Dewatering (2007 only) and fluridone application from 2007 through 2012 plus a low-density grass carp stocking in 2013 resulted in a 100% tuber density decrease in the Tar River Reservoir. Two tubers recovered in fall 2012 were assumed to be 6 yr or older, and were still viable. On the unmanaged Shearon Harris Reservoir, average whole-lake tuber densities ranged from 838 to 2,050 tubers sq m^{-1} from 2008 to 2013. Lake Gaston sites subjected to fluridone treatment every other year demonstrated a tubers m^{-2} bank reduction of 28% after 2 yr and 63% after 4 yr. Conversely, Lake Gaston sites that were treated consecutively exhibited a 75% tuber density reduction in 2 yr and a 93% reduction after 3 yr. Based on these data it would take five alternate-year treatment cycles to match the tuber reduction reached in three consecutive-year treatments. Tuber densities as low as 11 m^{-2} were adequate for a significant recovery in biomass and a 1,136% increase in new tuber production in just one season. Results suggest that by managing the tuber bank there is the potential to conserve management resources by switching to less intensive and costly strategies when densities are deemed to be at a nonnuisance level.

Key words: aquatic herbicides, fluridone, hydrilla, tuber.

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INTRODUCTION

Hydrilla verticillata (L.f.) Royle has been described as the "perfect aquatic weed" (Langeland 1996), and also has the distinction of being "one of the world's worst aquatic weeds" (Shearer and Jackson 2006). This opportunistic submersed macrophyte has spread from its native range in Asia to every continent except Antarctica (Pieterse 1981, Cook and Luond 1982). Hydrilla has been able to spread long distances because of adaptations in reproduction, growth, and physiology, as well as assistance from human activities (Langeland 1996, Chadwell and Engelhardt 2008). Monoecious hydrilla, one of two biotypes found in the United States, is well established in North Carolina and can be found as far north as Maine and as far west as Washington. Both monoecious and dioecious hydrilla were found coexisting in Lake Gaston, NC in the mid-1990s (Ryan et al. 1995); however, since the initial discovery only monoecious hydrilla has been observed on the lake.

Hydrilla is able to reproduce both sexually through seed, and asexually through fragmentation and turions (Langeland 1996). Turions have been suggested as the most important source of hydrilla regrowth (Haller et al. 1976). Hydrilla produces turions on both the leaf axil (axillary turions) as well as subterranean turions on terminal ends of rhizomes, hereby called tubers (Langeland 1996). Axillary turions are short, covered with scale leaves and small spines, and weigh 36 to 77 mg (Spencer et al. 1987). It has been speculated that small turion size facilitates spread to unaffected areas of a water body (Van and Steward 1990). Axillary turions are relatively short lived, with Van and Steward (1990) reporting survivability to be 1 yr or less. The majority of hydrilla propagule research has focused on tubers, due in part to the fact that they represent the key target in breaking the life cycle of hydrilla (Netherland 1997). Tubers allow hydrilla to withstand abiotic, biotic, and anthropocentric stresses (Netherland 1997). Tuber anatomy has been described as meristematic tissue enveloped in layers of leaf scales (Netherland 1997).

Monoecious tubers can vary from 30 to 320 mg in weight and have been found in densities of up to 1,312 tubers m^{-2} in the field (Table 1) (Hodson et al. 1984, Harlan et al. 1985). Under optimum mesocosm growing conditions, a single monoecious tuber produced 6,046 tubers over 16 wk (Sutton et al. 1992). Long-term hydrilla management is difficult because of tuber persistence in the hydrosoil, which Van and Steward (1990) reported to be up to 4 yr for monoecious propagules in southern Florida. This long-term

Table 1. Previous hydrilla tuber density studies.

Tuber Densities (Tubers sq m^{-1})	Hydrilla Biotype	Citation
Mesocosm		
2,099–9,053	Monoecious	Steward and Van (1987)
1,784–6,046	Monoecious	Sutton et al. (1992)
2,153	Dioecious	Steward and Van (1987)
3,524	Dioecious	Sutton et al. (1992)
Field		
200–1,312	Monoecious	Harlan et al. (1985)
703–1,312	Monoecious	Hodson et al. (1984)
20–510	Dioecious	Bowes et al. (1979)
300–600	Dioecious	Miller et al. (1976)

persistence does not constitute true dormancy because sprouting can be induced by a wide array of environmental factors (Netherland and Haller 2006).

Monoecious hydrilla has become established in many North Carolina Piedmont reservoirs where it quickly spreads across the littoral zone. Rapid expansion can lead to hydrilla infestations too expansive to be chemically treated each year with limited state and local funding. In the case of Lake Gaston, an average of 596 ha of hydrilla was present each year from 2007 to 2013, whereas only 493 ha per year, on average, were chemically treated for the same time period. This management was biomass driven with treatment areas being designated solely on the previous year's vegetation survey. This strategy resulted in sites being treated every other year or less frequently. It is thought a shift to tuber bank management could result in efficiency gains; however, more information on monoecious hydrilla tuber bank response to management practices must precede such planning.

Hydrilla biomass management has been extensively studied, whereas the management of tubers has not. Because tubers cannot be directly targeted, tuber density reduction requires tuber sprouting to occur, followed by timely elimination of hydrilla shoots so that new tuber formation is prevented. Grass carp and herbicides have been found to do this effectively, thus reducing tuber densities over time (Sutton and Vandiver 1986). Sutton (1996) found successful herbicide applications in combination with grass carp reduced dioecious hydrilla tuber densities from 887 to 0 tubers m^{-2} in 4 yr in the North New River Canal, Florida. Similar work with monoecious hydrilla has not been reported. In addition, very few field studies have monitored tuber densities during active *in situ* management (Van and Vandiver 1992, Langeland 1993). Therefore, our objective was to monitor tuber densities on several sites with different management regimes over multiple years.

MATERIALS AND METHODS

Four Piedmont reservoirs (Figure 1) were selected for monitoring, each with varying amounts of hydrilla coverage, management inputs, and treatment regimes. Core sampling was initiated in 2007 for Tar River Reservoir and Lake Gaston and in 2008 for Shearon Harris Lake and Lake Tillery (Table 2). The timing of sampling was based on the phenology of the plant. As monoecious hydrilla behaves as a herbaceous perennial, dying back completely each fall, the most opportune time to sample tubers is from late fall to early spring. The present-year tubers have been formed and there is little to no sprouting occurring. Sampling points were selected based on established tuber populations and GPS coordinates of each point were recorded. All water bodies with the exception of Lake Gaston were managed on an annual basis (Table 3).

Sampling was conducted with the use of a 10.2-cm-diam sediment core puller modified from Sutton (1982). Each core sampled roughly 0.008 m^2. Harlan et al. (1985) reported that 93 to 100% of monoecious hydrilla tubers were found in the top 12 cm of hydrosoil; therefore, the target depth for each sample was approximately 20 cm. All core samples were sifted through 3-mm wire screen to recover and count all tubers and turions. The number of cores pulled per site varied over time (Table 3) to adjust for diminishing tuber populations, as recommended by Spencer (1994).

Shearon Harris Lake is located just southwest of Raleigh, North Carolina and is 1,660 ha in size. Hydrilla has been present in the lake for roughly 20 yr and no organized aquatic vegetation management has occurred in recent years. Therefore, this reservoir was utilized as a reference site because of the lack of management activities. Tuber bank sampling was conducted seven times in 6 yr (Table 2) at five sampling points, with a total of 890 core samples taken.

The Tar River Reservoir is located near the town of Rocky Mount, North Carolina and is the town's primary potable water supply. Approximately 135 ha of hydrilla were confirmed in an upper branch of the reservoir in 2005. The Tar River Reservoir was treated annually with fluridone from 2007 to 2012 and was dewatered in summer 2007 because of drought conditions after the application of fluridone. No fluridone application was made in 2013; however, a low stocking rate of grass carp was introduced (approximately 1.5 fish per original hydrilla hectare). Tuber sampling was initiated on the Tar River Reservoir in April 2007 and samples were taken a total of 12 times (Table 2) at five sampling points with a total of 4,495 core samples taken. All five points were sampled each year except 2014. In 2014 only the single point, where tubers were found in 2012, was sampled, with 500 core samples taken.

Lake Tillery reservoir is a Pee Dee River impoundment in the western Piedmont region of North Carolina. This lake is approximately 2,025 ha in size and has a relatively incipient infestation of hydrilla, approximately 60 ha, that was originally discovered in 2006. Herbicide treatments were applied annually from 2008 to 2011, and grass carp were introduced in 2009 with a target of 44.5 fish per vegetated hectare. A supplemental stocking occurred in 2010 to maintain the stocking rate. Initial Lake Tillery tuber sampling occurred in December 2008 (Table 2) and a total of seven sampling events were conducted from 2008 to 2014, with a total of 1,052 core samples taken. Five sampling points, in a 10-ha area, were established on the reservoir and the number of samples pulled ranged from 10 to 30.

Lake Gaston is an 8,100-ha reservoir that straddles the North Carolina and Virginia border. This lake is the central of three Roanoke River hydroelectric impoundments.

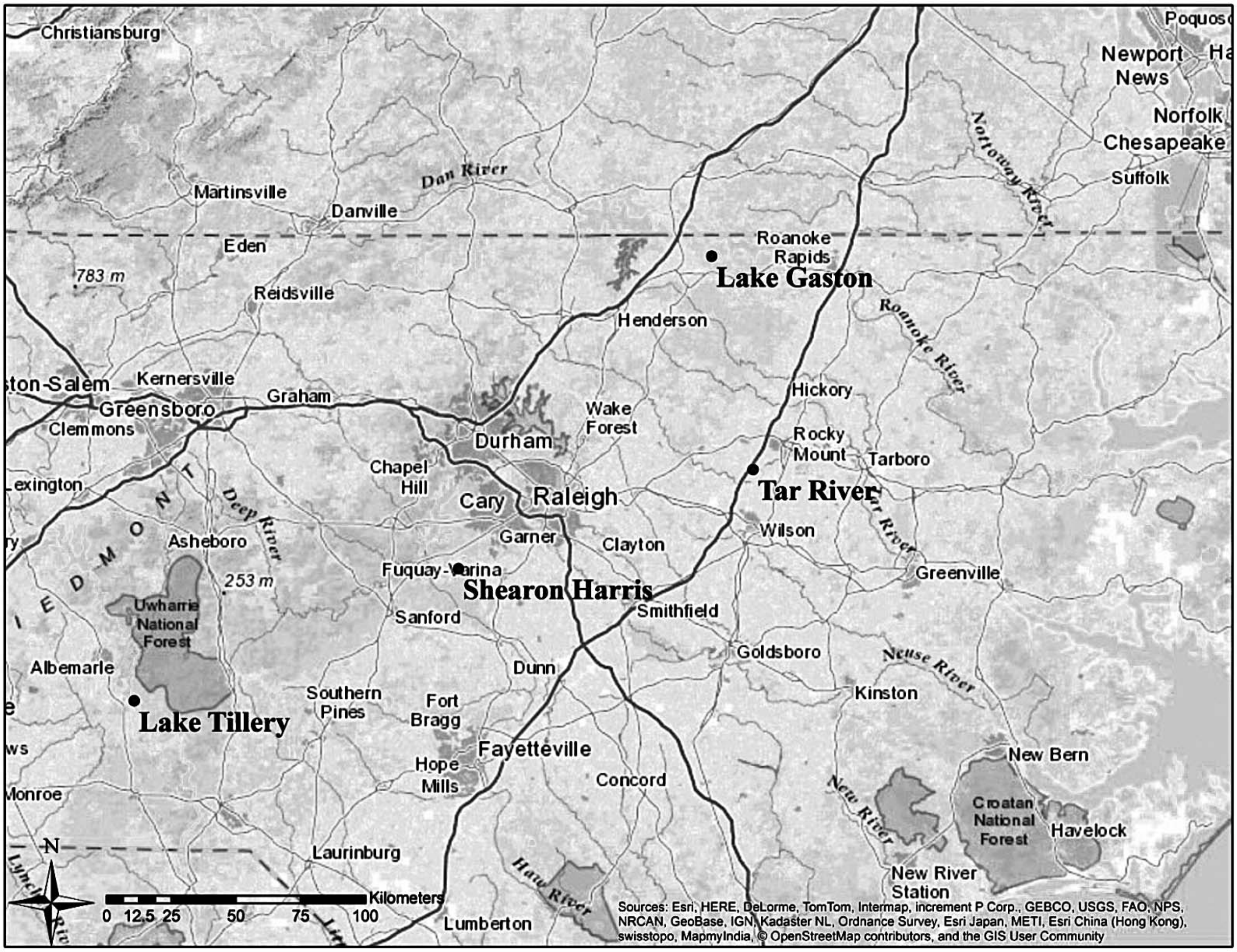

Figure 1. Location of the four tuber sampling sites, Lake Gaston, Lake Tillery, Shearon HarrisLake and Tar River Reservoir.

Hydrilla was first discovered in the lake in the mid-1980s and infested approximately 618 ha in the fall of 2011 (Remetrix, 2012). Lake Gaston hydrilla management strategies have included a combination of herbicides and triploid grass carp. Numerous grass carp stockings have occurred since the discovery of hydrilla, and the current target density is 46 fish per vegetated hydrilla hectare. Annual large-scale fluridone treatments also occur on Lake Gaston. Because of the large hydrilla area and limited funding, it has been common practice to rotate herbicide treatments among sites, with only a few sites receiving consecutive-year treatments over the course of this study.

Lake Gaston tuber sampling was initiated in May 2007 (Table 2) and a total of 11 sampling events were conducted from 2007 to 2013. Nine sites (Figure 2), encompassing approximately 275 ha, and a total of 36 points (Table 3) were sampled with 10 to 50 samples per point, and a total of 10,705 core samples taken. An assessment of tuber bank response to alternate-year or consecutive-year herbicide treatment was conducted in 2007 and 2008. Three sites were selected for treatment in 2007, but not in 2008 (Cold Springs, Hawtree, and Poe). These alternate-year treatment sites each had four sampling points. Three sites were selected for treatment in both 2007 and 2008 (Hubquarter,

Table 2. Tuber sampling dates for Lake Gaston, Shearon Harris Lake, Tar River Reservoir, and Lake Tillery.

Site	2007	2008	2009	2010	2011	2012	2013	2014
Lake Gaston	May, November	April, June, November	April, November	November	December	December	December	
Shearon Harris Lake	–	May, October	–	March, October	October	December	December	
Tar River Reservoir	April, June, July, November	April, October	April	March, October	October	November	–	January
Lake Tillery	–	May, December	December	October	October	December	–	March

Table 3. Treatment regime, number of sampling points, and number of cores pulled per point for all tuber sampling sites (2007 through 2014).

Water Body	Site	No. of Sampling Points	Range of No. of Cores Pulled per Sampling Point	Total No. of Cores Pulled	Treatment
Lake Gaston	Cold Springs	4	10–30	1,148	Alternate
	Hawtree	4	10–30	1,155	Alternate
	Poe	4	10–30	1,176	Alternate
	Hubquarter	5	10–50	1,543	Consecutive
	Lyons	4	10–50	1,313	Consecutive
	Smith	4	10–50	1,219	Consecutive
	Cotton	3	10–30	836	Control
	Hamlin	4	10–30	1,160	Control
	Lakeview	4	10–30	1,155	Control
Shearon Harris Lake	–	5	10–30	1,040	Control
Tar River Reservoir	–	5	15–500	4,495	Consecutive
Lake Tillery	–	5	10–30	1,052	Consecutive

Lyons, and Smith). Hubquarter had five sampling points, and Lyons and Smith each had four sampling points. Finally, three sites with no planned herbicide treatment were selected as controls (Cotton, Hamlin, and Lakeview). Cotton, because of its small size, had only three sampling points, while Hamlin and Lakeview each had four sampling points. Because of budgetary restrictions, consecutive treatments could not be continued in 2009; therefore,

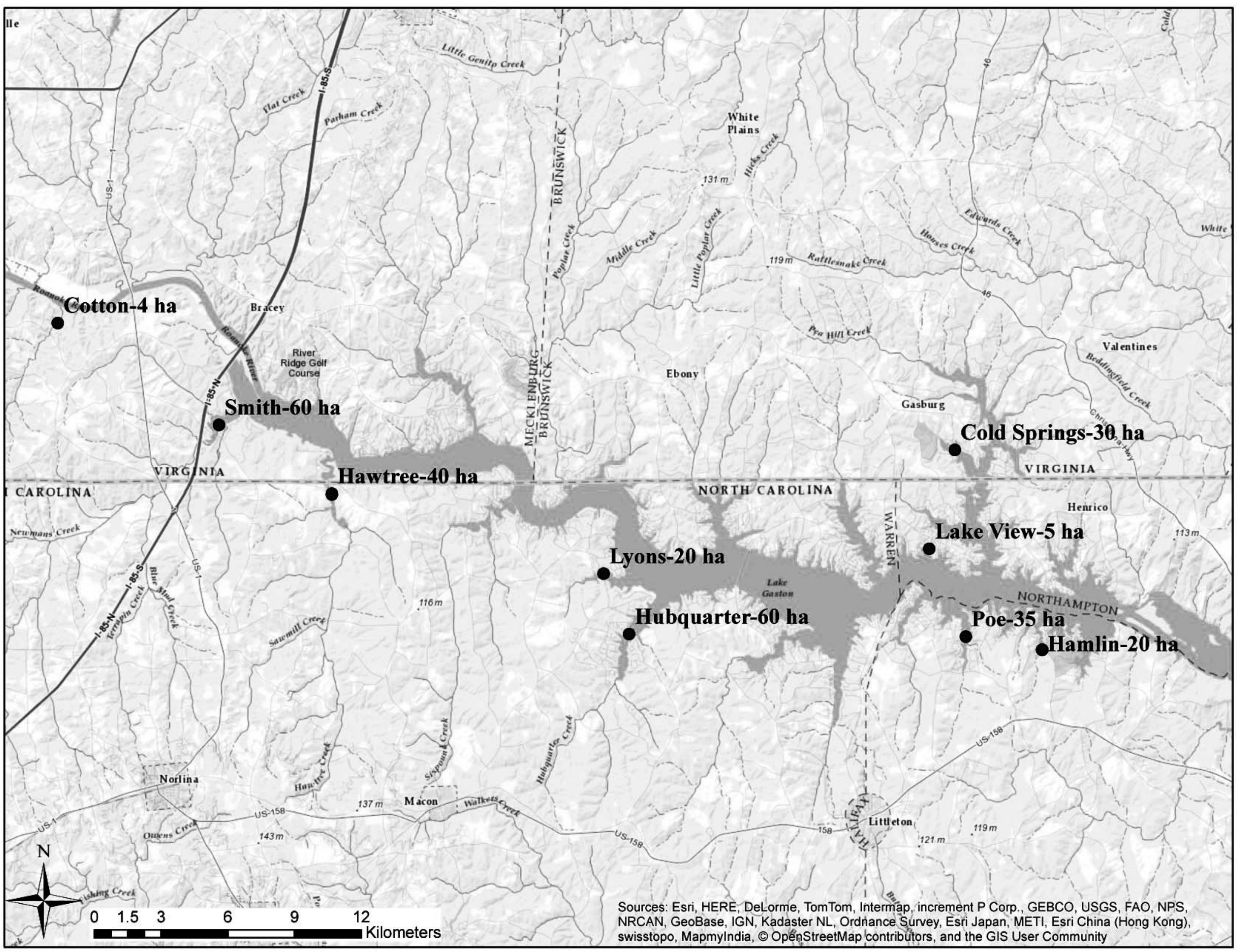

Figure 2. Location of the nine tuber sampling sites on Lake Gaston and corresponding acreages.

TABLE 4. AVERAGED TUBER DENSITIES AND STANDARD ERRORS IN TUBERS SQ M^{-1} FOR LAKE GASTON, SHEARON HARRIS LAKE, TAR RIVER RESERVOIR, AND LAKE TILLERY.[1,2]

Site	Cove	Tuber Density in Tubers sq m^{-1}							
		Initial	2007	2008	2009	2010	2011	2012	2013
Lake Gaston									
	Cold Springs	151± 48	108 ± 32 a*	167 ± 49 a	39 ± 26*	175 ± 121	19 ± 3*	35 ± 21	31 ± 24
	Hawtree	240 ± 83	160 ± 37 a*	199 ± 65 a	40 ± 33*	113 ± 63	143 ± 113	38 ± 30	214 ± 146
	Poe	693 ± 123	113 ± 19 a*	434 ± 124 a	102 ± 19*	147 ± 94	118 ± 63*	125 ± 68	98 ± 47
	Lyons	160 ± 62	105 ± 60 a*	40 ± 25 b*	11 ± 7*	136 ± 74	219 ± 109	294 ± 175	93 ± 43*
	Hubquarter	580 ± 203	153 ± 45 a*	122 ± 44 b*	423 ± 130	353 ± 89	108 ± 20*	108 ± 20	293 ± 133
	Smith	246 ± 93	167 ± 24 a*	84 ± 27 b*	56 ± 12	23 ± 9	83 ± 57	8 ± 6*	4 ± 4
	Cotton	189 ± 30	218 ± 43 b	587 ± 107 a	163 ± 52	463 ± 102	687 ± 111	218 ± 58	178 ± 18
	Hamlin	604 ± 168	971 ± 211 b	418 ± 132 a	369 ± 203	382 ± 93	604 ± 176	446 ± 88	336 ± 169
	Lakeview	253 ± 109	546 ± 150 b	309 ± 95 a	101 ± 33	201 ± 96	110 ± 55	124 ± 44	40 ± 19
	Flats	–	–	–	–	–	–	119 ± 78	86 ± 31*
Shearon Harris Lake	–	1,275 ± 249	–	1,705 ± 506	1139 ± 398	939 ± 368	839 ± 199	2,050 ± 502	1,056 ± 498
Tar River Reservoir	–	697 ± 84	299 ± 60*	78 ± 22*	32 ± 10*	3 ± 1*	2 ± 2*	0.08 ± 0.08*	0 ± 0
Lake Tillery	–	607 ± 358	–	566 ± 333*	343 ± 176*	213 ± 94*	19 ± 6	8 ± 4	4.11 ± 2.6

Means within columns with the same letter (a, b) are not significantly different according to the Tukey-Kramer honestly significant difference test ($P < 0.05$)
[1]Only fall samplings are displayed after the initial sampling.
[2]Asterisks denote treatment performed.

statistical comparisons between alternate- and consecutive-year treatments were limited to 2007 and 2008.

Tuber densities were calculated for each sampling period with the equation $T/(C/123.34)$, where T is the number of tubers recovered; C is the number of cores pulled, and 123.34 is the numbers of cores needed to sample 1 sq m. Tuber densities from each sampling point were averaged across each water body or, in the case of Lake Gaston, each site.

An analysis of variance (ANOVA) was run in SAS[1] to determine differences in tuber densities over time, or by treatment regime, for Shearon Harris Lake and Lake Gaston. If a significant difference was detected, treatment means were separated with the use of the Tukey-Kramer honestly significant difference (HSD) test. All analyses were conducted at a $P < 0.05$ level of significance. Prior to this analysis the corresponding data sets were subjected to an Anderson-Darling normality test with a significance level of $P < 0.05$. It was found that both data sets needed transformation; therefore, the square root of tuber densities was used. Data transformation increased P values from 0.009 to 0.08 in Shearon Harris and from < 0.005 to > 0.250 in Gaston, thus attaining heterogeneity in the distributions. A quadratic regression was also used on the Lake Gaston data set to analyze differences in the treatment regimes. In order to evaluate tuber bank attrition rate on Tar River Reservoir and Lake Tillery, a sigmoidal regression function was performed in Sigmaplot 12.1[2]. The data sets for these water bodies were also pooled, and the same analysis was conducted for comparison.

RESULTS AND DISCUSSION

Shearon Harris Lake

Shearon Harris whole-lake tuber densities ranged from 839 to 2,050 m^{-2} and 1,250 m^{-2} for the 6 yr of sampling (Table 4). The greatest density recovered was 3,243 m^{-2} at one sampling point in fall 2011. These whole-lake and single-point densities are considerably greater than any previously reported field study on hydrilla (Table 1). No significant variation ($F = 0.936$, $P = 0.505$, ANOVA) was found in comparing tuber density means over the entire 6 yr of sampling (Table 4). The extended infestation period and the lack of organized management likely indicates that tuber carrying capacity has been reached in this lake. Year-to-year variability in tuber density may be explained by flucuations in available nutrients, water quality, available light, or other environmental factors that affect hydrilla growth and reproduction. Sutton and Portier (1985) suggested a steady-state tuber density is possible when the number produced is equal to the number germinated and lost to decay. They also stated this density would be dependent on sediment type, available nutrients, and water quality. Given the high proportion of monoecious tubers that sprout each season, signficant new production is required on a seasonal basis.

Lake Tillery and Tar River Reservoir

Lake Tillery and the Tar River Reservoir both received effective annual herbicide treatments with a transition to triploid grass carp. Tubers recovered had likely been formed prior to treatment and dewatering, as these management activities effectively removed hydrilla shoot biomass each year and prevented new tuber production (Heilman 2007, Mark Heilman, Sepro Corp., pers. comm.). Initial tuber densities were found to be similar in both water bodies with the use of $F = 0.05$, $P = 0.82$ (ANOVA). When tuber densities were pooled across water bodies, a similar and significant trend was observed ($R^2 = 0.84$, $P < 0.0001$) (Figure 3). Tuber density decrease was rapid during the first 2 yr, followed by a longer period of small annual decreases. At 5 yr after initial sampling, the tuber density decrease was approximately 96%. On the Tar River Reservoir, tuber density decreases at years 1 and 2 were 74 and 93%, respectively (Figure 4). The following 5 yr of management only resulted in an additional 5.57% reduction from the initial density. This extended period of tuber persistence can greatly increase the cost of management and result in

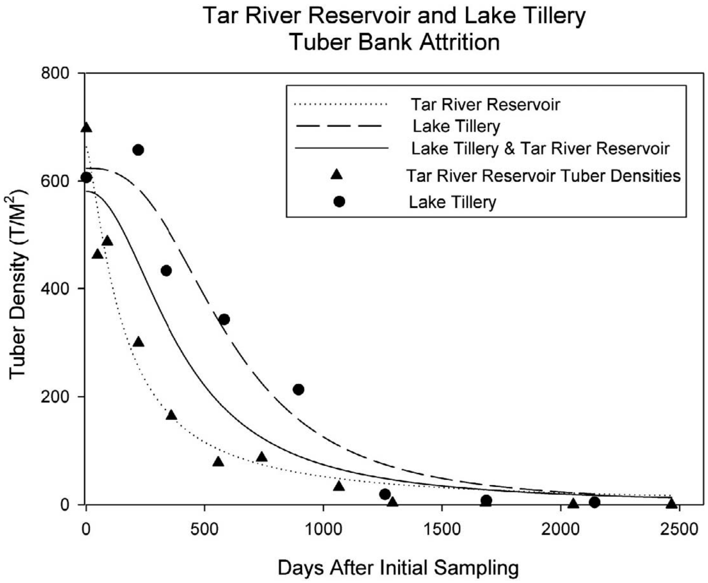

Figure 3. Sigmoidal regression analysis for tuber densities in the Tar River Reservoir, Lake Tillery and combined data sets. Tar River Reservoir, Lake Tillery and combined data sets all had well-fit significant results ($R^2 = 0.9751$, $P < 0.0001$; $R^2 = 0.9607$, $P = 0.0003$; $R^2 = 0.8351$, $P < 0.0001$), respectively. The well-fit combined model shows similar tuber attrition rates are expected in geographically similar systems with similar management practices.

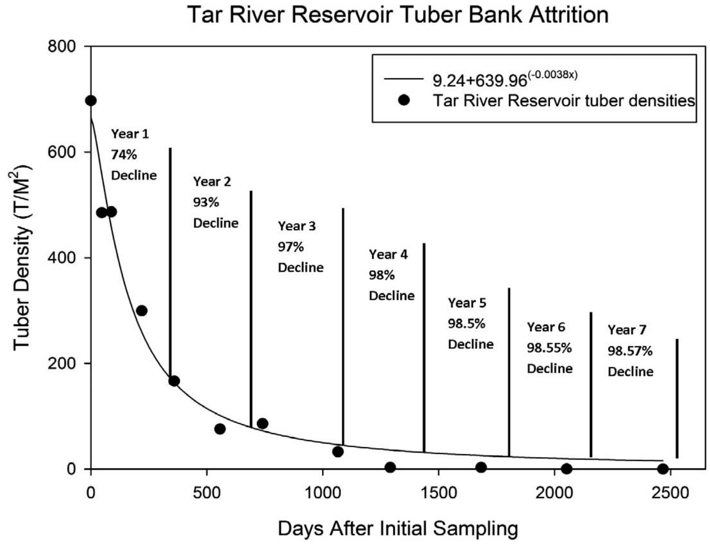

Figure 4. Observed and predicted decline of the averaged tuber bank density in the Tar River Reservoir.

miniscule gains of tuber bank attrition. Future research is needed to investigate the threshold at which active management could be reduced or halted based on tuber density resulting in nonnuisance levels of hydrilla.

Our results are consistent with a study by Sutton (1996) on dioecious hydrilla in the North New River Canal in Florida where a combination of herbicides and grass carp ultimately eradicated the tuber bank. Herbicide treatments were sporadically effective at reducing tuber density; however, grass carp introduction resulted in a clear density reduction, ultimately leading to eradication (Sutton 1996). No such study showing consistent monoecious hydrilla tuber density declines has been previously reported. It was expected that monoecious hydrilla tuber banks undergoing the same management and in the same region would respond similarly. The comparison suggests that inferences can be made to tuber bank longevity in mid-Atlantic water bodies with similar management.

Two tubers were recovered during the last sampling event on Tar River Reservoir in fall 2012 suggesting an age of 6 yr or more. The two tubers recovered on this date both sprouted when placed in a greenhouse, which extends the known monoecious hydrilla dormancy from 4 yr to 6 (Van and Steward 1990). The time needed to deplete a tuber bank that is being intensively managed is dependent on tuber sprouting and mortality rates, which differs between hydrilla biotypes. Based on reported sprouting rates and static densities in the field, this time period could be substantially longer for dioecious hydrilla than we found for monoecious hydrilla (Haller et al. 1976, Miller 1976, Bowes 1979, Hodson 1984, Harlan 1985, Steward and Van 1987).

Lake Gaston

Initial tuber densities were assigned as baseline values for this lake. The baseline mean for the alternate year sites was 387 tuber m^{-2}, whereas the baseline mean of the consecutive sites was 348 tubers m^{-2}. ANOVA indicated no significant difference ($F = 0.024$, $P = 0.885$) between these means. In 2007, both alternate- and consecutive-year sites received herbicide treatment and no biomass was recovered from the treatment areas (Remetrix 2007). Tuber densities for the alternate- and consecutive-year treatment areas were found to respond similarly with no difference noted in the comparison ($F = 0.01$, $P = 0.926$, ANOVA). Tuber depletion rates for alternate- and consecutive-year sites in 2007 were 65 and 57%, respectively. Both treatment regimes were significantly different from the control (alternate year $F = 37.49$, $P = 0.0020$; consecutive year $F = 36.43$, $P = 0.0021$ HSD).

Herbicide treatment in consecutive sites had similar efficacy in 2008 to that observed in 2007 (Remetrix 2008). Only one survey point recovered hydrilla in 2008 (within Hubquarter Creek); thus tuber replenishment was believed to be minimal. Tuber densities in consecutively treated sites declined to less than 40% of original levels over the 2 yr (Figure 5). Lack of treatment in alternate-year sites in 2008 resulted in hydrilla biomass resurgence, which returned tuber densities to approximately 78% of original levels. This divergence in tuber densities of the alternate versus consecutive-year treatment sites was found to be significant ($F = 7.26$, $P = 0.0378$ HSD). In fall 2008, tuber densities in the alternate-year treatment sites were similar to the control sites ($F = 2.47$, $P = 0.1651$ HSD), whereas the consecutive-year sites were reduced by 75% and were significantly different from the control sites ($F = 17.63$, $P = 0.0052$ HSD). This illustrates the regenerative capacity of the tuber bank when management pressure is released early in a management cycle. Attrition rates for the two treatment strategies were equivalent in year 1, but distinctly greater on sites

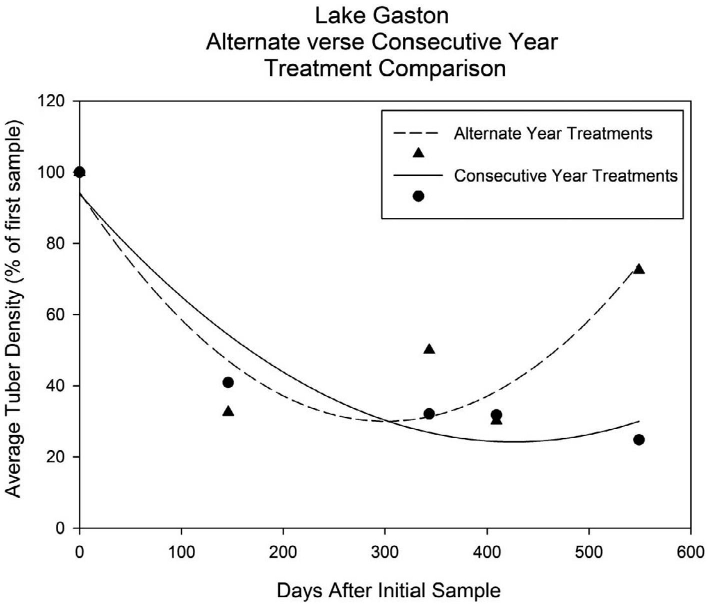

Figure 5. Quadratic regression models and averaged values of tuber densities for alternate-year (R^2 = 0.91; P = 0.043) treatment and consecutive-year (R^2 = 0.99; P = 0.031) treatment sites on Lake Gaston.

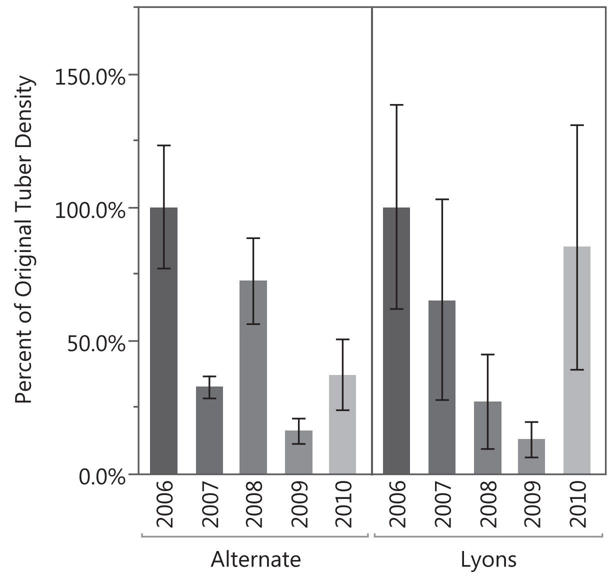

Figure 6. Tuber density means and standard errors for alternate-year treatment sites (Cold Springs, Hawtree, and Poe), which received treatments in 2007 and 2009, and the consecutively treated site Lyons, which received treatment from 2007 through 2009.

released from management at the end of year 2. Political pressure when budgetary restrictions do not allow whole-lake treatment could result in management alternating between sites. Based on our data, it would take approximately five alternate-year treatment cycles to reduce tuber density to the same level as was obtained by two consecutively applied treatments, resulting in greater management expense. By monitoring and managing the tuber bank instead of strictly biomass as was traditionally done, managers would conserve resources and deplete the tuber bank more rapidly. Managers could focus resources on depleting the greatest tuber densities first and using less intensive (and less costly) management on sites with lower tuber numbers.

Budget limitations in 2009 resulted in only one cycle of alternate and consecutive-year treatment comparison across all preselected sites. Alternate-year treatments continued on all three coves for another cycle, similar to historic treatment frequency. Results for 2009 and 2010 are consistent with those from 2007 and 2008 for alternate-year treatments resulting in an average yearly tuber density decrease of 63% over the 4-yr period (Figure 6). Examining this treatment frequency pattern for 4 yr shows both tuber bank depletion and substantial replenishment. This management practice did successfully reduce tuber densities, but it also perpetuated the infestation for at least another 6 yr. The release of management pressure, even for as little as a year, can result in as much as a fourfold increase in densities on individual sites. This was documented in Poe creek from 2007 to 2008 (Table 4).

Lyons Creek, which had an initial tuber density of 160 tuber m^{-2}, was treated with herbicide for 3 consecutive years before ceasing in 2010. A 93% decrease in tuber densities was observed over that 3-yr treatment period resulting in 11 tubers m^{-2}. A single year of no treatment resulted in an increase to 85% of the original density (Figure 6) or 136 tubers m^{-2} (Table 4).

A consideration for long-term hydrilla management or eradication efforts is reaching a threshold where the tuber density is low enough to transition from herbicides to other less intensive management options. This study demonstrates that even a tuber bank of 11 tubers m^{-2} with a moderate stocking rate of grass carp still has the potential to increase rapidly during a single season. There is likely a sliding scale of densities that would constitute this threshold, and they are likely different for each water body, based on unique environmental, water, and site characteristics. As such any transition in strategy should be combined with extensive and rigorous monitoring to ensure no biomass is allowed to persist long enough to produce tubers and extend management needs. Being able to adapt management based on tuber densities could potentially conserve management resources. For instance, after depressing the tuber bank to a desired level through successful annual herbicide treatment, a shift could be made to a low stocking rate of grass carp in conjunction with more frequent monitoring.

SOURCES OF MATERIALS

[1]SAS statistical software, Version 9.3, SAS Institute Inc., Cary, NC 27513.

[2]Sigma Plot 12, Systat Software Inc., San Jose, CA 95110.

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