Analysis of Grass Carp Dynamics to Optimize Hydrilla Control in an Appalachian Reservoir

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Abstract

The primary objectives of this study were: 1) to evaluate the movement patterns, habitat use, and survival of triploid grass carp *Ctenopharyngodon idella* stocked to control hydrilla *Hydrilla verticillata* in a riverine reservoir (Claytor Lake, Virginia), 2) to examine grass carp population dynamics and hydrilla growth dynamics in Claytor Lake to guide long-term management efforts, and 3) to describe the aquatic plant community in the New River upstream of Claytor Lake to assess the potential for alterations due to potential grass carp herbivory. Only 3% of radio-tagged grass migrated out of Claytor Lake during the 2-year study. Grass carp movement patterns were significantly correlated with temperature-, weather-, and habitat-related variables. Grass carp selected specific cove, shoal and tributary habitats colonized by hydrilla. First-year survival of grass carp was 44% in 2011, and 25% in 2012. Grass carp growth rates were rapid in 2011, but declined in 2012 concurrent with significant reductions in hydrilla abundance. Based on grass carp population dynamics observed in Claytor Lake, our stocking model predicted that hydrilla could be controlled through 2030 by a grass carp standing stock of 5-6 metric tons. We documented 12 plant species in the New River upstream of Claytor Lake, 9 of which are preferred plants for grass carp suggesting that the plant community could be altered if migration rates increase. Grass carp can be effective for managing hydrilla in riverine reservoirs; however, continued monitoring of grass carp population dynamics, migration rates, and vegetation abundance could facilitate greater precision in management efforts.

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Chapter 1: Introduction

Problem statement

Invasive species are a primary threat to fisheries production and ecosystem integrity at all scales (Elton 1958, Coblentz 1990, Moyle and Light 1996, Gordon 1998). In USA lakes, one of the most detrimental invasive aquatic weeds is hydrilla *Hydrilla verticillata*. Since hydrilla's introduction during the 1960s in Florida (Blackburn et al. 1969) it has spread to over 2,800 waterbodies across 30 states (USGS 2009; EDDMapS 2013). Once established, hydrilla infestations prove detrimental to industrial and recreational water uses through clogged irrigation channels and water-intakes, and a reduction in boating and swimming opportunities (Langeland 1996). Management of hydrilla infestations can be highly site-specific and often requires an integrated approach that can include herbicide application, mechanical manipulation, and biological control using triploid grass carp (Madsen 1997).

Hydrilla became established in Claytor Lake, Pulaski County, VA in 2003, and rapidly expanded in areal coverage. Stakeholders lobbied the Virginia Department of Game and Inland Fisheries (VDGIF) to stock triploid grass carp *Ctenopharyngodon idella* in 2011 to help control the hydrilla infestation. Grass carp have been used as a biological control agent to treat hydrilla infestations for several decades (Shireman and Maceina 1981, Killgore et al. 1998, Chilton and Magnelia 2002). However, the use of grass carp in large reservoirs can yield highly variable results in levels of control due to uncertainty in optimal stocking densities, and stocked grass carp dynamics. For example, grass carp stocking densities reported in the literature range from 3 to 638 fish per vegetated ha to achieve vegetation control (Sutton and Vandiver 1986, Stewart and Boyd 1999). Furthermore, little is known about grass carp population dynamics or behavior in temperate, riverine reservoirs like Claytor Lake. Grass carp are native to large river systems of East Asia, and have shown the ability to make long migrations upstream during periods of high flows (Fischer and Lyakhnovic 1973, Guillory and Gasaway 1978, Gorbach and Krykhtin 1988). Upstream of Claytor Lake, the New River is unimpeded for 39 river-km and sustains a trophy sportfishery for several game fish species. If a significant number of grass carp migrate they could potentially reduce ecologically important vegetation thereby leading to negative effects on the sportfishery within this stretch of the New River.

Hydrilla management in the United States

Hydrilla as an invasive species

Hydrilla is a member of the monocot family Hydrocharitaceae (Bowmer et al. 1995) native to most of Asia, Australia, and the Pacific Islands (Cook and Luond 1982; Madier et al. 2007. Since its initial introduction into the United States, hydrilla has been documented in all Gulf Coast states, Atlantic Coast states as far north as Maryland and Delaware, in the western states of California, Washington, and Arizona and on every continent except Antarctica (Langeland 1996; Shabana et al. 2003).

Hydrilla is highly adaptive and tolerant of a wide array of environmental conditions, and possesses the ability to reproduce through multiple strategies (Langeland 1996). Hydrilla can grow in water as deep as 14.3 m (Yeo et al. 1984), oligotrophic and eutrophic conditions (Cook and Luond 1982), pH ranging from 5 to 9 (Steward 1991), and relatively high salinities (Haller et al. 1974). Once hydrilla becomes established in an aquatic ecosystem, it typically spreads rapidly through multiple reproduction modes including fragmentation, root crowns, rhizome and stolon growth, or production of subterranean turions (tubers) and axillary turions (Puri et al. 2007). Furthermore, almost 50% of hydrilla fragments with a single whorl of leaves can germinate a new plant capable of producing a new population (Langeland and Sutton 1980).

Van and Steward (1990) found that axillary turions are viable for one year, and subterranean tubers can persist for up to four years in sediment. Hydrilla found in the United States was considered dioecious until 1982, when the first monecious plants were discovered in the Potomac River (Steward et al. 1984). Monecious plants possess the ability to produce viable seeds, although seed production is lower in temperate regions than in the tropics (Lal and Gopal 1993). Both monecious and dioecious plants have been documented in Lake Gaston, an impoundment of the Roanoke River in Virginia-North Carolina (Ryan et al. 1995). Once established in a system, hydrilla forms a dense, entangled surface mat, and rapidly dominates the native aquatic flora.

Submersed aquatic vegetation (SAV) is beneficial to fish and other aquatic organisms at intermediate levels of coverage (20-30%; Colle and Shireman 1980; Durocher et al. 1984; Bettoli et al. 1992), thus hydrilla infestations can be perceived as beneficial by sportfish anglers in systems where native vegetation abundance is low. However, the fast growth and multiple reproductive strategies exhibited by hydrilla generally result in the rapid expansion of dense, monotypic stands within a waterbody. Accordingly, Colle and Shireman (1980) found that adult largemouth bass (*Micropterus salmoides*) in hydrilla-infested lakes in Florida showed a reduction in condition factor when vegetation coverage was greater than 30% of total lake area, presumably due to decreased predation efficiency. Expansive hydrilla coverage may also limit angling opportunities and angler success within a lake or reservoir. For example, catch rates of largemouth bass declined along with angler effort as hydrilla surface coverage increased to 65 percent in Lake Seminole, FL (Slipke et al. 1998). Thus the focus of hydrilla management is often to reduce hydrilla coverage to desirable levels without eradicating all vegetation within a system (Leslie et al. 1987; Bain 1993; Chilton and Magnelia 2008).

Methods of controlling hydrilla

Mechanical methods to manage hydrilla include biomass removal, drawdowns, dredging, and bottom sealing (Barko et al. 1986; Doyle and Smart 2001). Drawdowns in reservoir systems have been shown to stimulate germination in 80% of tubers, although to be an effective management tool multiple drawdown events must occur in concert (Netherland 1999, Doyle and Smart 2001). Furthermore, drawdowns may negatively affect native vegetation or strand sessile benthic faunal taxa (e.g. mussels). The most commonly implemented mechanical method is biomass harvest. However, the harvesting equipment can cost $200,000 to 300,000 USD with operating costs estimated at $2,000 USD acre^{-1} (Claytor Lake Technical Advisory Committee, unpublished data). Biomass harvesting can provide four weeks of hydrilla control during the growing season (Fox and Haller 1992), with up to six harvests required annually (McGehee 1979). Haller et al. (1980) estimated that biomass harvest activities have direct impacts upon a fishery, with an estimated 18% fish biomass loss valued at $6,000 USD acre^{-1} harvested.

Herbicide applications are another commonly used method for managing nuisance vegetation such as hydrilla. Research on potential chemical treatments for hydrilla began in Florida in the 1960’s. An early study by Blackburn and Weldon (1970) documented five contact herbicides that provided temporary control of hydrilla in field experiments, although only diquat plus copper sulfate was apparently non-toxic to fish. Endothall, another contact herbicide, has also been used to treat aquatic vegetation for over 40 years and can be effective on hydrilla (Macdonald et al. 2002). The advantages of contact herbicides are that they require short contact times and can be used to treat localized areas (Madsen 2000). Fluridone is a nonselective systemic aquatic herbicide that requires very long exposure times, but may be effective at very low concentrations on hydrilla (Madsen 2000). However, long contact times required for treatment have facilitated evolution of Fluridone-resistant hydrilla populations in short periods of time (Pons 2005). Futhermore, Fluridone is only effective in lentic areas that allow for adequate contact times (Madsen 2000) and can cost \$1,000 USD acre^{-1} (Claytor Lake Technical Advisory Committee, unpublished data). Additionally, herbicide treatments can damage non-target plant species, and may be viewed negatively by the public (Madsen 2000).

Numerous studies have focused on identifying biological control methods to manage hydrilla. Biological control is founded on the theory that all organisms have a natural enemy, where natural-enemy populations have the unique ability to interact with their prey or host populations more efficiently than non-natural predators (Debach 1974). Biological control strategies in the United States have used insects, pathogens, and vertebrates to reduce pest problems. Several insects and pathogens have been evaluated as potential biological control agents for hydrilla. For example, weevils in the genus *Bagous* are important natural enemies of hydrilla in Pakistan (Baloch et al. 1980; Balciunis and Minno 1985), and introductions have occurred in Florida, Alabama, and Texas to control hydrilla with limited success (Madsen 1997). The fungal pathogen *Mycoleptodiscus terrestris* has shown promise as a control agent for hydrilla. This pathogen acts as a contact mycoherbicide that rapidly digests hydrilla, and can be integrated with Fluridone treatments for increased effectiveness (Madsen 1997).

The herbivorous grass carp has proven to be an extremely effective biological control agent for managing hydrilla. Grass carp are native to larger coastal rivers of East Asia with a large latitudinal range stretching from 20 to 50º N and 100 to 140º E (Fischer and Lyakhnovic 1973; Pipalova 2006). In their native range grass carp typically attain weights of 30 to 36 kg, although fish up to 181 kg have been reported (Lopinot 1972; Chilton and Muoneke 1992). Interest in use of grass carp as a biological control agent stems from their successful propagation in aquaculture settings, their propensity to consume undesirable submersed vegetation, and the potential to convert excess plant growth into marketable fish (Sutton 1974). Grass carp possess large pharyngeal teeth that move in forward-and-backward motions and are specifically adapted for vegetation consumption (Prowse 1971). They are considered voracious herbivores and can consume more than their body weight in vegetation daily (Verigin et al. 1963; Kilambi and Robison 1979). Grass carp display large variability in diet selectivity for vegetation types (Chilton and Muoneke 1992); however, submerged, soft-leaved vegetation such as hydrilla are frequently preferred (Sutton and Vandiver 1986; Pine and Anderson 1989; Pine and Anderson 1991). In addition, grass carp diet selection is affected by demographic and ecological factors such as fish size and age, water temperature, vegetation availability, ecosystem size, and grass carp population size (Opuszynski and Shireman 1995; Cudmore and Mandrak 2004).

Biological control using grass carp

Grass carp use in the United States

Interest in the use of grass carp for vegetation control in the United States was initiated by Swingle in 1957 (Mitchell and Kelly 2006), and in 1963 the first grass carp arrived in Arkansas. By 1970 grass carp had been stocked into lakes in Arkansas, Alabama, Arizona, Florida, Louisiana, and Georgia (Mitchell and Kelly 2006). Researchers originally believed that natural reproduction of grass carp could not occur in the United States (Pierce 1983); however a study by Stanley et al. (1978) concluded that grass carp had the potential to reproduce. Conner et al. (1980) documented natural reproduction in the Mississippi River, thereby initiating controversy over the use of diploid grass carp and their potential impact on aquatic ecosystems and leading restrictions on their use in many states (Sutton 1977). Cassani and Canton (1986) developed a method of heat-and-cold shock shortly after fertilization that produced 100% triploid (sterile) grass carp, opening the door to looser regulations on the use of the triploid grass carp for vegetation control.

Hydrilla management using grass carp generally requires the identification of a specific stocking density aimed at achieving management goals; however, reported densities and associated changes in hydrilla are highly variable. Grass carp stocking densities are generally reported as number of fish per lake surface area, vegetated area, or total plant biomass. Stocking rates of 3-638 fish per vegetated ha were reported as being effective for hydrilla removal in Florida (Sutton and Vandiver 1986). In small Texas impoundments grass carp stocked at only 7.5 fish per vegetated ha completely eradicated all submersed vegetation (Blackwell and Murphy 1996). Conversely, grass carp stocked at 180 fish per vegetated ha in Devils Lake, Oregon achieved only 30% control of vegetation (Bonar et al. 1993). These efforts have utilized a single large stocking event, while more-recent stocking strategies have found success using incremental stockings over time to achieve intermediate, desirable plant densities within a system (Bain 1993; Chilton and Magnelia 2008).

Movement of stocked grass carp

Within their native range grass carp are believed to be highly migratory, potentially reducing their effectiveness as a biological control agent in open systems of the United States. In the Amur River, Russia grass carp execute a slow migration of up to 500 km after spending their first 5 years feeding in the lower stretches (Gorbach and Krykhtin 1988). In the United States, Guillory and Gasaway (1978) found that grass carp unintentionally introduced into the Mississippi River completed migrations up to 1700 km. An observational study by Nixon and Miller (1978) concluded that lower water temperatures reduced movement of the tagged fish, and noted a resting pattern at night. Mitzner (1978) concluded that the grass carp were primarily sedentary with movement being associated with vegetation availability, and found no differences in movements between daylight and nocturnal periods. Clapp et al. (1993) used telemetry data to develop home-range estimates for grass carp in two large Florida lakes, and found that home ranges were larger in a sparsely vegetated lake than a lake with abundant vegetation. Another movement study indicated that grass carp exhibit a shoaling behavior particularly around vegetated areas, with longer movements between feeding locations occurring frequently (Hockin et al. 1989). Bain et al. (1990) found that movements were greater by adult grass carp when compared with juveniles, concluding that adults were less affected than juveniles by temperature declines, and showed less affinity for vegetation. Similarly, a movement study in several impoundments of the Guadalupe River, Texas showed that 59% of tagged fish emigrated during periods of high flows, with a maximum distance of 325 km (Prentice et al. 1998). Alternatively, research on adult grass carp movements in the Santee Cooper River, South Carolina showed average movement over a 2-year period of only 14.4 km (Kirk et al. 2001).

Population dynamics of grass carp

The formulation of a hydrilla management plan using grass carp requires an understanding of growth and mortality rates of these fish (Kirk and Socha 2003). Like other fishes, grass carp growth is related to a variety of factors such as temperature, hydrology, food availability, and population size. Kilambi and Robison (1979) found an optimal feeding range of 18-29º C, while Opuszynski (1972) found an optimum feeding range of 25-28º C. Grass carp rarely feed at temperatures below 3º C, while active feeding begins at 7-8º C (Michewicz et al. 1972; Chilton and Muoneke 1992). Growth of grass carp in its native Amur River was greatest in the first four years followed by incremental decreases in growth at subsequent ages (Chilton and Muoneke 1992). Similarly in the Santee-Cooper Reservoir, South Carolina, Morrow et al.

(1997) reported average annual growth in length of 150-200 mm y^{-1} for ages 1-3, but a decrease to 60-70 mm y^{-1} for ages 4-6. Growth rates for 200-mm stocked grass carp in hydrilla infested Lake Wales, Florida averaged 10.4 g d^{-1}, and average length was 962 mm by the fourth year (Shireman et al. 1980). Stocked grass carp in Lake Guntersville, Alabama showed growth rates of 140 mm y^{-1} at ages 1-4, upon which growth slowed to 22 mm y^{-1} in subsequent years (Morrow and Kirk 1995). Mitzner (1978) observed a 5.5 g d^{-1} weight increase in Red Haw Lake, Iowa, possibly indicating a latitudinal influence on grass carp growth rates. However, the absence of additional grass carp growth studies in the literature for more temperate regions of the United States preclude further assessment of variation.

Similar to growth, mortality rates of stocked grass carp also can vary due to myriad abiotic and biotic factors. Grass carp are tolerant of a wide range of water temperatures (0-39.3° C), and dissolved oxygen levels (down to 0.2 mg L^{-1}, Chilton and Muoneke 1992). A study by Shireman et al. (1978) found almost complete mortality of 5,000 48-mm grass carp stocked into a pond with largemouth bass, suggesting that predation can greatly increase mortality rates. Shireman et al. (1978) therefore recommended 450 mm TL as a size threshold for stocked grass carp to reduce predation mortality by largemouth bass. Alternatively, Stich (2011) found that grass carp 352 mm TL could be stocked without significant reductions to year-one survival. Stress from hauling and stocking also can impact grass carp mortality rates. Clapp et al. (1994) reported 6-27% mortality for grass carp hauled in the winter, and 15-52% mortality for spring hauling. Few studies have identified mortality rates for grass carp stocked in large waterbodies. Kirk and Socha (2003) reported annual mortality rates ranging from 22 to 39%, and maximum age of 14 y for triploid grass carp in the Santee Cooper Reservoir, South Carolina. Similarly, Stich et al. (2013) found mortality rates of 20-25%, and a maximum age of 16 y for grass carp in Lake Gaston, Virginia and North Carolina.

Study Site

Claytor Lake (Figure 1.1) is a 1,876-ha mainstream impoundment of the New River, located in the Valley and Ridge physiographic province, Pulaski County, Virginia. It is controlled by Appalachian Power, which generates electricity through a hydroelectric dam located on the northern end of the impoundment. The reservoir is 34 km long, has a maximum width of 0.8 km, shoreline development index of 10.65, maximum normal pool elevation of 563 m above sea level, and an average retention time of 33 days (Table 1.1; Rosebery 1951). The climate is generally classified as mountain temperate, and has a mean annual temperature of 11° C and mean annual precipitation of 928 mm (New LocClim 1.1; FAO/SDRN, Rome, Italy). The impoundment influence stretches 34 river-km from the dam at the north to a riffle at Allisonia in the southwest (Appalachian Power 2008). Buck Dam is the first impoundment upstream of Claytor Lake, between which the New River flows 39 km. Below Claytor Dam the river flows unimpeded for 113 km before entering the Bluestone Reservoir in West Virginia. The largest tributary to Claytor Lake is Peak Creek, which enters the main lake approximately 11 km upstream of Claytor Dam.

Claytor Lake is a public water source for Pulaski County, and provides a variety of water-based recreational activities for residents and visitors including fishing, swimming, boating, and wildlife viewing (Appalachian Power 2009). The sportfishery is relatively diverse and contains smallmouth bass *Micropterus dolomieu*, largemouth bass, spotted bass *Micropterus punctulatus*, striped bass *Morone saxatilis*, hybrid striped bass *Morone chrysops* x *Morone saxatilis*, yellow perch *Perca flavescens*, walleye *Sander vitreus*, flathead catfish *Pylodictus olivarus*, channel catfish *Ictalurus punctatus*, muskellunge *Esox masquinongy*, black crappie *Pomoxis nigromaculatus*, and sunfish *Lepomis spp.* There are four public access points along the length of the reservoir, and multiple fishing piers to provide recreational opportunities to users.

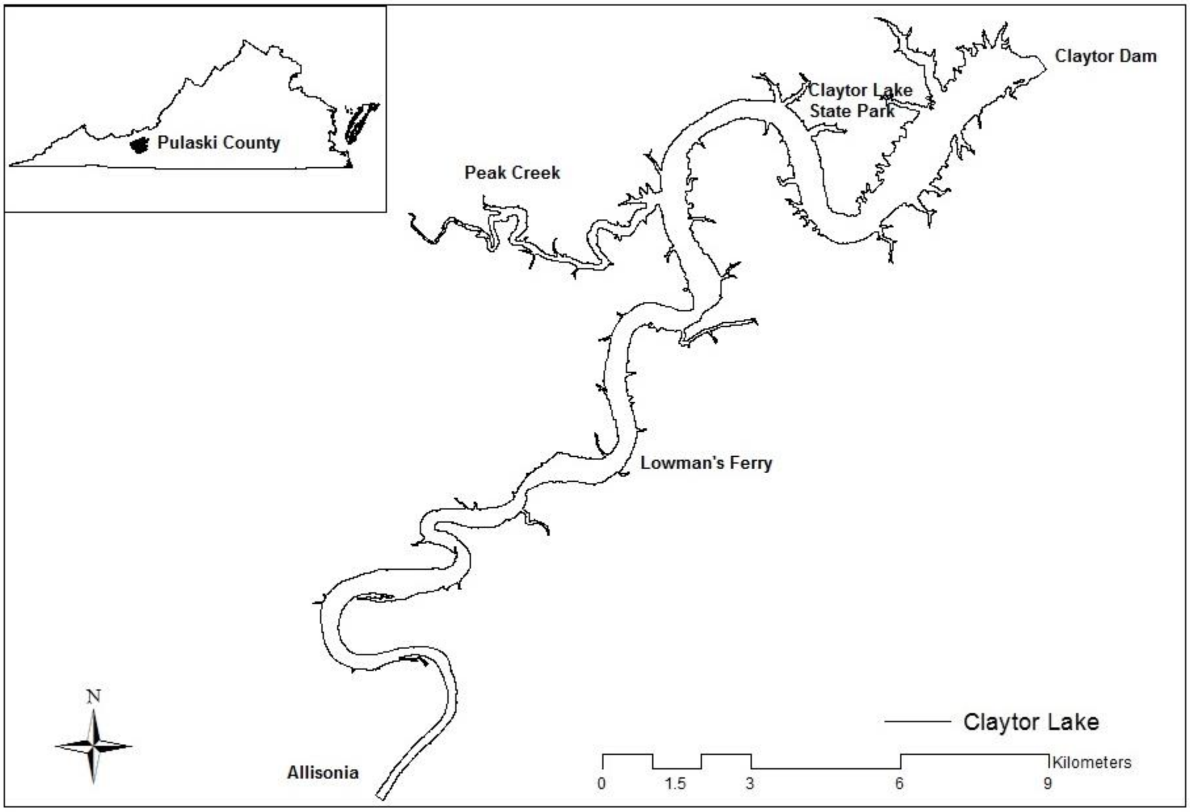

Figure 1.1 Map of Claytor Lake a 1,876-ha mainstream impoundment of the New River located in Pulaski County, Virginia, USA.

Table 1.1 Comparison of selected United States waterbodies where grass carp have been stocked to control hydrilla infestations.

Waterbody	State	Surface Area (ha)	Elevation (m)	Mean depth (m)	SDI[a]	GDD[b]	Physiographic province	Yr grass carp stocked
Claytor Lake	VA	1,876	563	15	10.65	1584	Valley and Ridge	2011
Lake Gaston	VA/NC	8,100	62	12.5	17.67	2410	Piedmont	1995
Lake Norman	NC	13,142	30	10.3	20.61	2425	Piedmont	2004
Lake James	NC	2,634	375	13.5	13.30	1106	Piedmont	2002
Lake Ouachita	AR	16,040	181	16.3	24.73	2395	Ouachita Mountains	2007
Lake Guntersville	AL	27,479	181	4.7	26.01	2689	Appalachian Plateau	1988
Lake Marion	SC	39,366	23	4	7.21	3046	Coastal Plain	1989
Lake Seminole	GA/FL	13,158	24	3.1	14.89	3457	Coastal Plain	1994
Lake Conway	FL	739	26	7.2	1.27	4636	Coastal Plain	1977
Lake Conroe	TX	8,100	61	6.4	7.92	3693	Coastal Plain	1981
Lake Austin	TX	648	150	3.7	4.28	3943	Great Plains	2003
Lake Texana	TX	4,453	13	4.7	8.51	3799	Coastal Plain	1989

[a]Shoreline development index, [b]Annual growing degree days

Aquatic vegetation community of Claytor Lake and the New River

Areal coverage of aquatic vegetation in Claytor Lake has historically been low (J.R. Copeland, Virginia Department of Game and Inland Fisheries (VDGIF), personal communication). Little information is available on the aquatic vegetation community in Claytor Lake, however Rosebery (1951) noted that variable water levels and steeply sloped shoreline habitat limits plant growth in the reservoir. In 2007 Appalachian Power conducted an aquatic vegetation study as part of the Federal Energy Regulatory Commission (FERC) relicensing requirements (Appalacian Power 2008). The study reported 117 ha of submerged aquatic vegetation in Claytor Lake and eleven aquatic plant species (Table 2). Three of the eleven species were classified as exotic: slender naiad *Najas minor*, hydrilla, and curly pondweed *Potamogeton crispus*. The only native plants identified as dominant species in the survey were

Canadian water weed *Elodea canadensis*, water celery *Valisneria americana*, and water-thread pondweed *Potamogeton diversifolius*. Studies are limited on the aquatic vegetation community in the New River above Claytor Lake as well. Hill and Webster (1982) noted that five species of aquatic macrophytes were common in the New River: hornleaf riverweed *Podostemum ceratophyllum*, American water-willow *Justicia americana L.*, broadleaf cattail *Typha latifolia L.*, curly pondweed, and Canadian water weed. Hornleaf riverweed was the most dominant species, apparently due to the swift flowing, shallow bedrock riffle habitats of the New River (Hill and Webster 1984). No information regarding densities, areal coverage, or spatial distribution of macrophytes in the New River is currently available.

Table 1.2 Characteristics of submerged aquatic vegetation found within the Claytor Lake project during 2007 survey (Source: Appalachian Power 2008).

Common name	Scientific name	Relative frequency	Dominant	Depth range & (average) (ft)
Slender naiad*	*Najas minor*	55.7%	54.5%	0.8-12.5 (4.4)
Hydrilla*	*Hydrilla verticillata*	37.6%	23.6%	0.8-12.5 (3.8)
Water weed	*Elodea canadensis*	16.1%	14.5%	1.0-7.0 (4.1)
Water celery	*Valisneria americana*	8.7%	3.6%	1.9-6.9 (4.6)
Long-leaf pondweed	*Potamogeton nodosus*	7.4%		0.8-5.3 (3.4)
Curly pondweed*	*Potamogeton crispus*	4.7%		1.0-5.8 (3.4)
Algae	*Algae*	4.0%		2.9-5.3 (3.8)
Water-thread pondweed	*Potamogeton diversifolius*	4.0%	1.8%	1.9-5.1 (3.5)
Muskgrass	*Chara sp.*	3.4%		0.8-5.1 (2.9)
Leafy pondweed	*Potamogeton foliosus*	2.7%		4.9-6.4 (5.6)
Small pondweed	*Potamogeton pusillus*	2.7%		2.2-6.0 (4.3)
Bare		9.4%	1.8%	

*Introduced species

Hydrilla in Claytor Lake

Hydrilla was discovered near Brown’s Hollow in Claytor Lake by VDGIF biologists in 2003, covering an estimated 16 surface ha (J.R. Copeland,VDGIF, personal communication).

The 2007 vegetation study by Appalachian Power found hydrilla in 25 of the 50 transects sampled, of which eight transects were classified as monotypic stands of hydrilla. In 2010, the Pulaski County GIS department estimated hydrilla coverage at 162 ha through photointerpretation of aerial imagery (J.R. Copeland,VDGIF, personal communication), a tenfold increase since 2003. Results of the 2010 survey found that a majority of the total hydrilla coverage was in the riverine portion of Claytor Lake where habitat was conducive to hydrilla establishment. In the lower portion of the lake, hydrilla continued to spread down the northwest shoreline and coves. Biologists from VDGIF estimate that hydrilla coverage in Claytor Lake may reach 405 ha if left untreated (J.R. Copeland, VDGIF, unpublished data).

The first chemical treatments aimed at reducing hydrilla coverage occurred in 2004 downstream of Allisonia in upper Claytor Lake (J.R. Copeland, VDGIF, personal communication). By 2007 public use areas around Claytor Lake State Park were being treated annually with chemicals. In 2010, the Claytor Lake Technical Advisory Committee (CLTAC) began work on developing a plan for long-term management of hydrilla in Claytor Lake (CLTAC, unpublished data). The CLTAC is composed of a diverse group of public and private organizations including: VDGIF, Virginia Department of Environmental Quality (VDEQ), Virginia Department of Conservation and Recreation (VDCR), Appalachian Power, Pulaski County, Friends of Claytor Lake (FOCL), Virginia Cooperative Extension, and Biological Monitoring Inc., Blacksburg, Virginia. In 2011, the CLTAC drafted a hydrilla management plan recommending the use of grass carp to reduce the hydrilla coverage to a controlled level of approximately 40 ha of areal coverage. However, uncertainty regarding grass carp movement and migration potential, population dynamics, and stocking densities in a novel environment such as Claytor Lake suggest a greater understanding of these factors is required to achieve hydrilla management goals. Therefore, VDGIF's approval for grass carp stocking into Claytor Lake was contingent upon research aimed at addressing these uncertainties.

Study objectives

To aid managers in achieving goals set forth by the CLTAC, and address concerns held by the VDGIF, we developed three primary objectives for the present study. Our first objective was to evaluate grass carp movement patterns, habitat use, and survival through a multi-year telemetry study to determine the efficacy of grass carp for controlling hydrilla in a highly riverine system like Claytor Lake. Our second objective was to examine grass carp population dynamics and hydrilla growth dynamics in Claytor Lake to guide long-term grass carp and hydrilla management activities in the lake. Our final objective was to describe the aquatic macrophyte community within the New River upstream of Claytor Lake to assess the potential for grass carp herbivory to alter the plant community structure if high rates of grass carp migration occur.

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Chapter 2: Analysis of grass carp movement patterns, habitat use, and survival in an Appalachian reservoir

Abstract

Grass carp *Ctenopharyngodon idella* have been introduced widely in the USA to control aquatic weeds including hydrilla *Hydrilla verticillata*. Grass carp have exhibited migratory behavior in river systems within their native range, and in the United States. Fisheries managers are concerned that grass carp stocked into Claytor Lake, Pulaski County, Virginia, a highly riverine reservoir, may exhibit similar migratory behavior thus limiting their efficacy as a biological control on hydrilla, and potentially altering the native plant community in adjacent river reaches. Furthermore, survival rates of stocked grass carp are rarely assessed despite their importance in guiding long-term management. Therefore, we conducted a multi-year telemetry study concurrent with annual grass carp stockings in Claytor Lake to investigate the migration potential, habitat use, and annual survival rates of grass carp stocked into a riverine reservoir system to control hydrilla. Thirty-four juvenile grass carp were radio-tagged in 2011, and 45 in 2012. Grass carp movement was greatest in the first month post-stocking and declined dramatically thereafter, presumably due to locating areas with hydrilla. Just 3% of radio-tagged grass carp migrated upstream into the New River during the study. Regression analysis indicated that grass carp movement patterns were significantly correlated with temperature-, weather-, and habitat-related variables. Radio-tagged grass carp selected for shoal, cove, and tributary habitats in Claytor Lake, each of which were known to be colonized by hydrilla. First-year survival for grass carp was estimated to be 44% in 2011, and 25% in 2012. Our results indicate that grass carp stocked into a riverine reservoir primarily utilize hydrilla infested areas, and that initial grass carp migration rates are minimal. However, as grass carp approach maturity migration rates

could increase, thus an examination of adult grass carp movement would be beneficial in determining the long-term efficacy of grass carp management in riverine reservoir systems.

Introduction

Grass carp *Ctenopharyngodon idella* have become widely distributed throughout the United States due to their use as a biological control for aquatic weeds including hydrilla *Hydrilla verticillata* (Shireman and Maceina 1981; Killgore et al. 1998; Chilton and Magnelia 2008). Grass carp are native to large coastal rivers in East Asia (Fischer and Lyakhnovic 1973; Pipalova 2006), and were first introduced to the United States in 1963 (Mitchell and Kelly 2006). The development of triploid (sterile) grass carp in the 1980's (Cassani and Canton 1986) eased concerns regarding grass carp reproduction in open systems thereby facilitating the use of grass carp to manage aquatic weeds in large reservoirs throughout the United States. The goals of aquatic weed management in reservoirs often focus on reducing vegetation levels without eradication, although reaching this goal has proven difficult (Noble et al. 1986, Leslie et al. 1996, Bonar et al. 2002). Thus a greater understanding of grass carp movement patterns, habitat use, and survival within a waterbody could aid in achieving such goals.

Fisheries managers could benefit from greater knowledge regarding grass carp movement patterns and habitat use as current knowledge on these topics is inconclusive and sometimes contradictory. In reservoir environments, an understanding of grass carp migration potential and habitat use may provide important insight into their affinity for target vegetation, and also the potential for non-target plants in adjacent waterways to be affected. In their native range, grass carp can migrate up to 500 km upstream (Fischer and Lyakhnovic 1973; Guillory and Gasaway 1978; Gorbach and Krykhtin 1988). In the United States, grass carp introduced into the Mississippi River migrated up to 1700 km (Guillory and Gasaway 1978) possibly indicating the tendency for grass carp to migrate may be enhanced in a riverine reservoir setting. Previous telemetry studies examining grass carp movement patterns and migration potential in large, reservoirs of the United States have produced variable results. In Lake Marion, South Carolina stocked juvenile grass carp demonstrated no preference for riverine habitat, and overall movements were primarily localized over a 2-yr study period (Kirk et al. 1996). Grass carp movements in two Texas reservoirs were initially high, but after an acclimation period movements decreased significantly apparently due to fish locating vegetated habitat (Chilton and Poarch 1997). Conversely, adult grass carp stocked in Florida and Alabama reservoirs exhibited long-range migrations in both upstream and downstream directions possibly indicating that grass carp movement patterns and habitat use varies by life-stage (Bain et al. 1990; Maciena et al. 1999). Variability among these studies suggests that grass carp habitat use, movement patterns and migration potential are often site-specific. Therefore greater characterization of these factors in a riverine reservoir with a more-temperate climate than prior studies conducted in lower latitudes could provide an important case study for future grass carp management in new systems.

A limited number of studies have characterized survival of stocked grass carp in reservoirs despite its importance in guiding long-term management strategies. Once stocked into a system, grass carp have proven elusive to standard fisheries sampling methods, often precluding the development of survival estimates. Bowfishing has shown promise as a collection technique in several large reservoirs, thereby facilitating the development of catch-curve analyses to estimate grass carp survival. However, this approach requires extensive effort by cooperators, along with numerous stocking years to produce survival estimates (Morrow et al 1997; Kirk et al. 2000). Alternatively, use of radio-telemetry allows researchers to estimate survival of various fish species instantaneously throughout a study, which can be beneficial for adapting grass carp stocking regimes based on observed survival, and hydrilla control levels (Hightower et al. 2001; Pollock et al. 2004). Grass carp survival rates ranged from 61-80% in sprawling reservoirs with extensive hydrilla infestations located in the Piedmont and Coastal Plain physiographic provinces with humid, subtropical climates (Morrow et al 1997; Kirk et al. 2000; Stich et al. 2013). Vegetation abundance in a system provides food resources and refugia for grass carp, and can be influenced by regional climate. Thus an investigation of grass carp survival in Claytor Lake, Pulaski County, Virginia with a moderate hydrilla infestation, and a more-temperate climate could provide important insight into grass carp survival rates among systems.

Hydrilla was first documented in Claytor Lake, an impoundment of the New River, in 2003 and rapidly expanded its coverage to 162 hectares ha by 2010. In 2011, the Virginia Department of Game and Inland Fisheries (VDGIF) approved the introduction of triploid grass carp to manage the rapidly expanding hydrilla upon recommendation of the Claytor Lake Technical Advisory Committee (CLTAC). However, VDGIF biologists were concerned the riverine morphology of Claytor Lake may elevate grass carp migration potential, thereby negatively affecting the aquatic plant community and highly valued sportfishery within the adjacent upstream reach of the New River. Therefore, we initiated a multi-year telemetry study concurrent with annual grass carp stockings to investigate overall movement patterns, migration potential, habitat use, and annual survival rates of grass carp stocked into a riverine reservoir system to control hydrilla.

Methods

Study Site

Claytor Lake (Figure 2.1) is a 1,876-ha mainstream impoundment of the New River, located in the Valley and Ridge physiographic province. Water levels are controlled by Appalachian Power (a subsidiary of American Electric Power Company, Inc., Columbus, Ohio), which generates electricity through a hydroelectric dam located on the northern end of the impoundment. The reservoir is 34 km long, has a maximum width of 0.8 km, mean depth of 15 m, max depth of 38 m, shoreline development index of 10.65, maximum normal pool elevation of 563 m above sea level, and an average retention time of 33 days (Rosebery 1951). The riverine zone of the reservoir extends approximately 15 km downstream from the head of the lake at the Allisonia rapids, and is defined by a shallow main channel and expansive shoal areas. The lacustrine zone begins at Lowman’s Ferry Bridge and extends the remaining 19 km downstream, with littoral areas generally limited to the far ends of coves and tributaries due to characteristically steep shoreline topography. Upstream of Claytor Lake, the New River is unimpeded for 39 km to Buck Dam. Downstream of Claytor Lake, the New River flows unimpeded for 113 km before entering Bluestone Reservoir, West Virginia. Hydrilla was first documented near Old Hurst Road in upper Claytor Lake, and by 2010 covered approximately 124 ha in shoal areas in the riverine zone and 38 ha across numerous coves and small tributaries near Claytor Lake State Park (Figure 2.1).

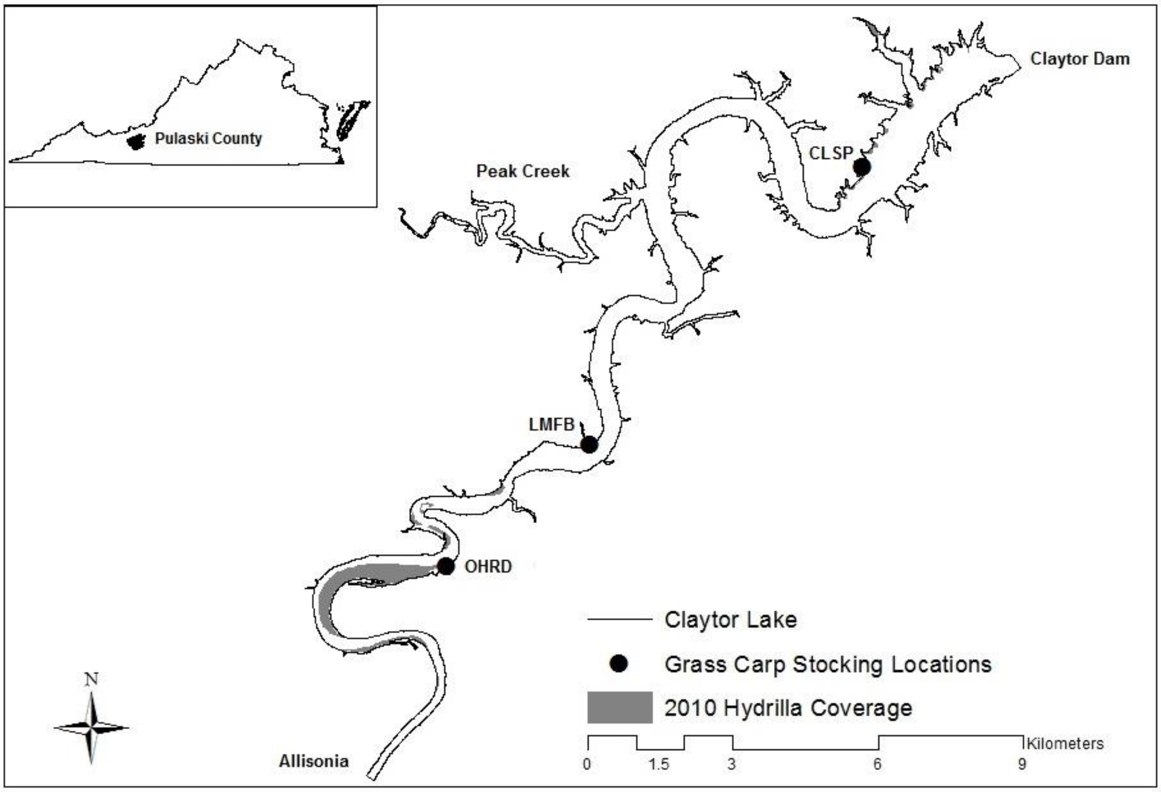


Figure 2.1. Map of Claytor Lake, Pulaski County, Virginia, USA including hydrilla coverage documented in 2010, and grass carp stocking locations Claytor Lake State Park (CLSP), Lowman's Ferry Bridge (LMFB), and Old Hurst Rd (OHRD) used in 2011.

Annual hydrilla coverage surveys

Lakewide estimates of hydrilla coverage were completed in October 2011 and October 2012 to monitor for potential changes in hydrilla coverage due to grass carp herbivory. Hydrilla beds were delineated from a boat using a depth sounder, and a double-sided rake attached to a rope that was tossed periodically to verify bed edges. A hand-held Garmin GPS Map76Csx (Garmin International Inc., Olathe, Kansas) unit was used to delineate the perimeter of each bed, and these coordinates were loaded into ArcGIS (ESRI, Redlands, CA) to determine areal coverage of hydrilla in Claytor Lake.

Radio-telemetry of stocked grass carp

We used radio-telemetry to study grass carp movement in Claytor Lake due to its demonstrated performance in large vegetated waterbodies, and in lotic environments (Winter 1996). In spring 2011, 34 triploid grass carp at of least 440 mm total length (TL) and 770 g were fitted with external saddle-mount radio transmitters by VDGIF biologists (Table 2.1), concurrent with a stocking of 6,000 grass carp for use as a biological control for hydrilla. Larger grass carp were chosen for radio-tagging to limit potential predation by largemouth bass *Micropterus salmoides* (Shireman et al. 1978). The grass carp were released at three locations to encourage dispersal to targeted hydrilla sites: half at Claytor Lake State Park (CLSP), one-quarter at Lowman's Ferry Bridge (LMFB), and one-quarter at Old Hurst Road (OHRD, Figure 2.1). An additional 45 externally radio-tagged grass carp were released in spring 2012 coinciding with a 3,000 fish maintenance stocking (Table 2.1). The grass carp radio-tagged in 2012 were evenly distributed among the three stocking sites. In 2011, we used Advanced Telemetry Systems (ATS, Inc., Isanti, Minnesota) Model F1820 40 pulse-per-minute (PPM) radio-tags modified to attach externally to the grass carp. For each tag, loops created with 11.3-kg monofilament line were secured to the transmitter with epoxy. Stainless steel wire was then attached to the loops and passed through the dorsal musculature of each grass carp and secured on the alternate side. The radio-tags were equipped with a mortality signal (80 PPM) that was triggered after 12 hours of inactivity. In 2012, we used ATS Model F2060 external mount radio tags also programmed with mortality sensors. We compared size-at-stocking of radio-tagged grass carp used in 2011 and 2012 using a two-sample t-test ($\alpha=0.05$).

Between May 2011 and April 2013 all radio-tagged grass carp were located approximately monthly. Fish were tracked primarily by boat with two bow-mounted Yagi antennas connected to a Lotek (Lotek Wireless Inc., Newmarket, Ontario) Biotracker scanning receiver. If a fish was not located during boat searches, areas upstream of Claytor Lake were searched by driving along the New River Trail, which parallels the New River from the head of the lake to the first upstream impoundment. Areas downstream of Claytor Dam were searched from the air. To maintain consistency in tracking intervals (Rogers and White 2008) tracking events generally lasted 2-4 days depending on seasonal conditions. We considered a radio-tagged grass carp to be located when reducing the telemetry receiver's gain no longer resulted in reduced signal intensity. Upon location of a tagged fish, we recorded geographic coordinates (UTM, NAD 83, Zone 17 S) using a Garmin GPS Map76Csx with an accuracy of ± 5 m. Additional variables recorded at fish locations included water temperature, depth, Secchi depth, distance to nearest shoreline, and signal type (live or mortality). We determined whether grass carp were located in vegetated areas using ArcGIS to overlay live-fish locations on hydrilla coverage maps generated from our 2011 and 2012 survey. Further data obtained for the study included inflow data from the United States Geological Survey (USGS) gauging station near Allisonia, Virginia, discharge data from Claytor Dam provided by Appalachian Power, and local weather conditions obtained from the National Weather Service (NWS) weather station in Blacksburg, Virginia.

Analysis of grass carp movement patterns

We used the Euclidean distance traveled (UTM, km) between each tracking location to determine the minimum average monthly movement (AMM, km) for the 2011 and 2012 cohorts of radio-tagged grass carp. Radio-tagged grass carp were considered dead upon receipt of a consistent mortality signal, and a lack of tag movement beyond the spatial error of the GPS (±5 m). Radio-tagged grass carp that died within one month of release were removed from the analysis due to the likelihood that mortality was due to surgery-related complications, or tag loss (Hightower et al. 2001). Beyond the immediate post-stocking period, classifications between dead and live grass carp were made at the conclusion of the study based upon history of signal type and location.

In our analysis of grass carp movement patterns we used two-sample t-tests to compare the first- and second-year AMM of the 2011 stocking cohort, and first-year AMM of the 2012 stocking cohort to first-year AMM of the 2011 stocking cohort. Movement rates observed within the first month post-stocking were excluded from the intra-cohort comparison based on reports of atypically high rates of movement during the initial acclimation period (Bain et al. 1990; Chilton and Poarch 1997). We described first-month post-stocking dispersal patterns of radio-tagged grass carp by calculating cardinal directionality of locations from stocking sites (White and Garrot 1990). To characterize potential effects of abiotic and biotic conditions on grass carp movement patterns in Claytor Lake we summarized AMM for each cohort by tracking interval along with a suite of 14 variables including: water depth at location, Secchi depth, water temperature, air temperature, humidity, barometric pressure, wind speed, precipitation, inflow, discharge, daylength, days post-stocking, accumulated growing degree days, and presence or absence of vegetation. Because many of the weather variables are collinear, we used a principal components analysis (PCA) to reduce cohort-specific variables to 3-4 significant, uncorrelated principal component factors (eigenvalues >1) that describe the major variations among potential predictors (Rypel 2009; 2011). We used stepwise multiple linear regressions (MLR) of log-transformed AMM and significant principal component observations to identify potential factors influencing grass carp movement in Claytor Lake. Model selection for each cohort was based on minimized Akaike's information criterion corrected for small sample size ($AIC_{c;}$ Burnham and Anderson 2002).

Analysis of habitat use by radio-tagged grass carp

We used the program FishTel 1.4 developed by Rogers and White (2007) to analyze the distribution of radio-tagged grass carp locations, and to examine habitat use. The random distribution module of FishTel 1.4 calculates a mean variance between actual fish locations, and an equal number of random points constrained by the lake perimeter. Conceptually, if fish locations are random we would expect a small mean variance between actual locations and random points, and a large variance if fish locations are clustered. The spatial statistic module develops a mean variance distribution from random points (equal to the number of fish locations) iterated 10,000 times. It then estimates the probability that the mean variance is greater than that identified by the random distribution module (Rogers 1998; Rogers and White 2007). To investigate habitat use by each cohort of grass carp we first identified six major habitat types within Claytor Lake: river channel, shoals, coves, tributaries, mainstream-littoral, and mainstream-limnetic. Habitat types were identified using a bathymetric map in combination with field observations. We delineated each habitat type using ArcGIS, and overlaid the live-fish locations for each cohort to determine the total number of fish locations for each habitat type (White and Garrot 1990; Rogers 1998). We used the maximum likelihood chi-square module in FishTel 1.4 to test whether radio-tagged grass carp were using available habitat in proportion to availability or were selecting for specific habitat types (Manly et al. 1993; Rogers and White 2008). To determine which, if any, habitat types were selected, we used the selection ratios (wi) module in the program Fishtel 1.4, where $wi < 1$indicates avoidance of a particular habitat type, and $wi > 1$ suggests selection.

Analysis of grass carp survival

We used the known-fates analysis in program MARK (White and Burnham 1999) to develop survival estimates for radio-tagged grass carp stocked in 2011 and 2012. This program estimates the survival of radio-tagged animals as a maximum likelihood estimate based on binary encounter histories for each individual during a specified number of intervals, where individuals that die during a specific interval are censored for the duration of the study. Similarly, if a tagged individual is not located during a specific interval, it is censored for that interval and subsequent intervals until re-located. Key assumptions for this analysis were 1) survival times are independent for all tagged grass carp, 2) censoring of individual grass carp is random, 3) each individual had the same probability of survival and re-location during each interval, and 4) radio-tagged grass carp had the same probability of survival as non-tagged grass carp stocked in Claytor Lake (Pollock et al. 1989; Hightower et al. 2001). We developed first-year survival models for both stocking cohorts of radio-tagged grass carp; we also developed second-year survival models for the 2011 stocking cohort. We used minimized AIC_c and AIC_c weights for model selection between time-dependent and constant-survival models (Burnham and Anderson 2002).

Results

Annual hydrilla coverage surveys

In 2011 we documented 160 ha of hydrilla coverage in Claytor Lake indicating a 2 ha reduction from the fall 2010 estimate (Pulaski County GIS Department, unpublished data). We also noted an apparent reduction in hydrilla density within the expansive beds in shoal areas of Upper Claytor Lake. In 2012 we documented 99 ha of hydrilla coverage in Claytor Lake along with significant reductions in hydrilla density through a corresponding exclosure experiment

(Chapter 3). More notably, hydrilla was apparently eradicated from previously colonized coves and tributaries near Claytor Lake State Park. Thus hydrilla coverage was only present within the shoal areas of upper Claytor Lake in 2012.

Radio-telemetry of stocked grass carp

Radio-tagged grass carp released in 2011 were significantly larger in both length and weight than those tagged in 2012 (p<.0001, Table 2.1). Overall, we identified 295 locations for live grass carp tagged in 2011, and 257 for grass carp tagged in 2012. Three grass carp released in 2011 were never relocated despite repeated searches, including areas upstream and downstream of Claytor Lake. No fish from the 2011 stocking cohort were located outside the boundaries of Claytor Lake; however, two grass carp from the 2012 stocking cohort migrated upstream into the New River during summer 2012. One of the migrants moved approximately 0.92 river km upstream before ceasing movement and presumably dying, and the other moved approximately 8.33 river km upstream where it remained through the duration of the study. Overall, movement was greatest within one month post-stocking for both years. Movements ranged from 0-16 km month^{-1} for individual fish, with averages of 2.0 and 3.4 km month^{-1} for the 2011 and 2012 stocking cohorts, respectively (Figure 2.2). After the first month post-stocking, movements were reduced for both stocking cohorts, with a majority of the tagged fish exhibiting localized movements in areas where hydrilla was documented. Mean total distance traveled for the 2011 cohort was 6.14 km (range 1.12-20.57) over the 2-yr study, while total distance traveled by the 2012 cohort averaged 6.10 km (range 1.53-26.24) during their 1-yr in the lake.

Table 2.1. Demographics of grass carp stocked into Claytor Lake in May 2011 and April 2012 including grass carp used in a telemetry study (R), and grass carp stocked for biological control of hydrilla (B).

			Total length (mm)				Weight (g)			
Year	Type	*n*	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max
2011	R	34	494 (30)	495	440	563	1162 (202)	1153	776	1602
2011	B	60	393 (36)	395	320	462	603 (175)	577	310	954
2012	R	45	394 (15)	395	320	462	603 (33)	577	310	1052
2012	B	57	334 (27)	330	289	380	423 (106)	415	260	661

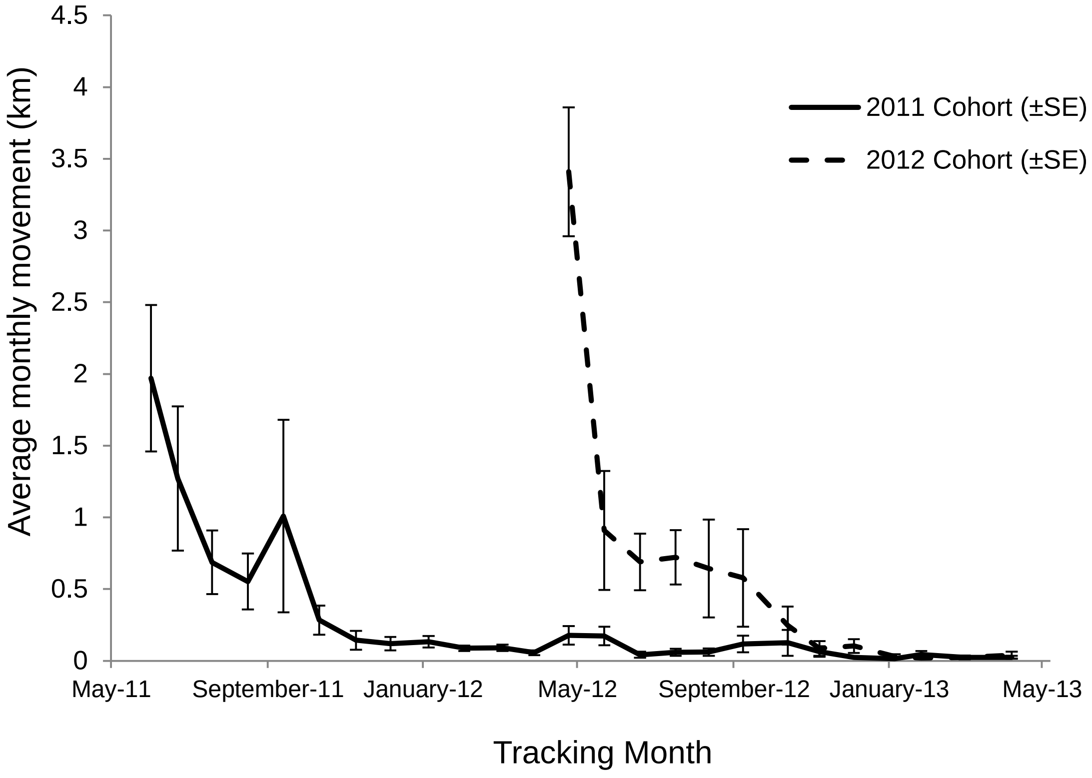


Figure 2.2. Average monthly movement (AMM, ±SE) observed for two stocking cohorts of radio-tagged grass carp in Claytor Lake between May-11 and April-13.

Analysis of grass carp movement patterns

The 2012 stocking cohort demonstrated greater dispersal than the 2011 stocking cohort within the first month after release; however, both cohorts appeared to exhibit an overall upstream trend in movement from stocking sites (Figure 2.3). There was no statistical difference between first- and second-year AMM rates for the 2011 stocking cohort (p=0.16), or between first-year AMM by the 2012 stocking cohort and first-year AMM by 2011 stocking cohort (p=0.68). Results of the PCA of environmental and biotic variables yielded four significant PC factors for the 2011 stocking cohort data set, and three significant PC factors for the 2012 stocking cohort data (Table 2.2). Based on contributions of variables determined from the PCA loading matrix, significant PC factors for the 2011 stocking cohort can be generally interpreted as temperature-related (PC1), flow-related (PC2), weather and habitat-related (PC3), and weather, habitat, and age-related (PC4) variables. Using similar interpretation, PC factors for the 2012 stocking cohort appear temperature and habitat-related (PC1), flow-related (PC2), and weather-related (PC3). Results of stepwise multiple regression for AMM and significant PC factors for each stocking cohort are shown in table 2.3. The best regression model for AMM of the 2011 stocking cohort included PC factors 1, 3, and 4 (r^2=0.55, p=0.001), whereas the best model for AMM of 2012 stocking cohort included PC factor 1 (r^2=0.96, p<0.0001) based on minimized $\mathrm{AIC_c}$ values (Table 2.4).

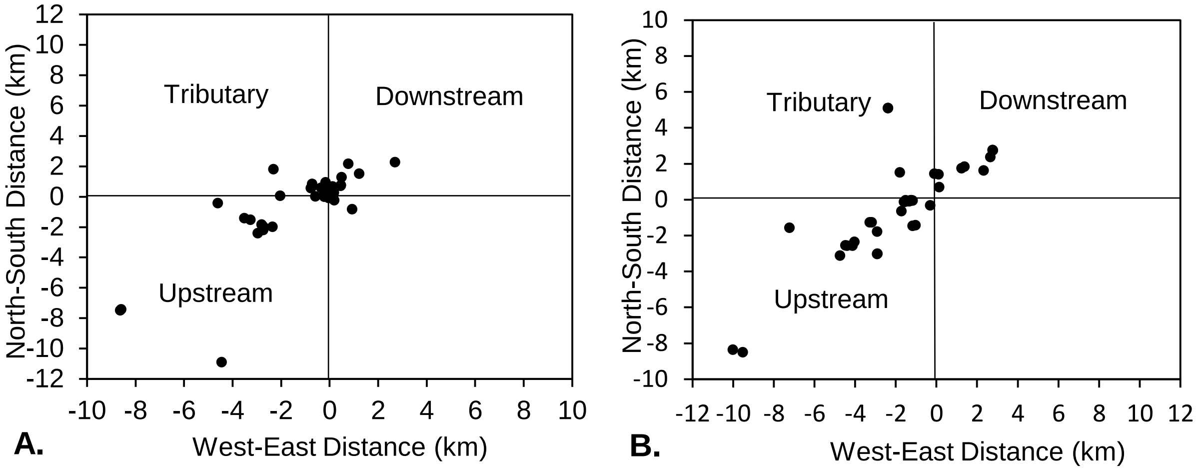


Figure 2.3. Post-stocking dispersal of the 2011 (A) and 2012 (B) stocking cohorts released into Claytor Lake. Generally, locations in the SW quadrant indicate upstream movement, locations in the NE quadrant indicate downstream movement, and locations in the NW quadrant indicate movement into major tributaries.

Table 2.2. PCA loading matrix and percent contribution (in parentheses) for 14 abiotic and biotic variables used to characterize observed movements of the 2011 and 2012 stocking cohorts in Claytor Lake. Bold indicates primary contributing variables for each principal component.

	2011 Cohort				2012 Cohort		
Variable	PC1	PC2	PC3	PC4	PC1	PC2	PC3
Water Depth	-0.43 (5.2)	-0.09 (2.0)	**-0.48 (13.3)**	**-0.56 (18.0)**	**-0.95 (9.3)**	-0.08 (1.9)	0.14 (5.2)
Secchi	-0.19 (2.4)	**-0.90 (20.4)**	0.04 (1.0)	0.20 (6.3)	-0.61 (6.0)	**-0.75 (17.5)**	-0.05 (1.8)
Water Temp	**0.92 (11.2)**	0.25 (5.6)	-0.21 (5.6)	0.08 (2.5)	**0.96 (9.4)**	0.11 (2.5)	-0.12 (4.3)
Air Temp	**0.97 (11.8)**	0.20 (4.5)	-0.11 (3.0)	0.03 (0.8)	**0.98 (9.6)**	0.04 (1.0)	-0.04 (1.6)
Humidity	0.53 (6.4)	-0.01 (0.2)	**0.53 (14.5)**	0.14 (4.5)	0.64 (6.2)	0.02 (0.4)	0.16 (5.8)
Bar Pressure	0.03 (0.4)	0.03 (0.7)	**0.72 (19.6)**	**-0.55 (17.6)**	0.12 (1.2)	-0.01 (0.2)	**0.96 (35.6)**
Wind Speed	**-0.86 (10.5)**	0.01 (0.2)	-0.21 (5.8)	**0.31 (10.0)**	-0.85 (8.3)	0.17 (4.0)	**-0.49 (17.9)**
Precip	-0.45 (5.5)	**0.75 (17.0)**	0.11 (2.9)	0.21 (6.8)	-0.46 (4.5)	**0.78 (18.2)**	0.11 (4.1)
Inflow	-0.68 (8.2)	**0.62 (14.0)**	0.04 (1.0)	-0.13 (4.1)	-0.43 (4.2)	**0.84 (19.6)**	0.15 (5.4)
Outflow	-0.72 (8.8)	**0.65 (14.8)**	-0.01 (0.3)	0.02 (0.6)	-0.52 (5.1)	**0.83 (19.3)**	-0.05 (1.8)
Daylength	0.81 (9.8)	0.36 (8.2)	-0.36 (9.8)	0.13 (4.0)	0.87 (8.5)	0.31 (7.2)	-0.25 (9.3)
Day Post-stocking	-0.48 (5.8)	-0.10(2.3)	0.20 (5.5)	**0.60 (19.1)**	-0.94 (9.2)	-0.07 (1.7)	-0.07 (2.5)
Accum GDD	**0.93 (11.4)**	0.25 (5.7)	-0.06 (1.8)	0.11 (3.5)	**0.95 (9.3)**	0.14 (3.2)	-0.06 (2.1)
Vegetated Area	0.20 (2.4)	0.20 (4.5)	**0.59 (16.0)**	0.07 (2.1)	**0.97 (9.5)**	0.14 (3.3)	-0.07 (2.6)

Table 2.3. Results of stepwise multiple regression for log-average monthly movement and significant PC factors from principal components analysis (PCA). Model selection was based on minimized AIC_c values.

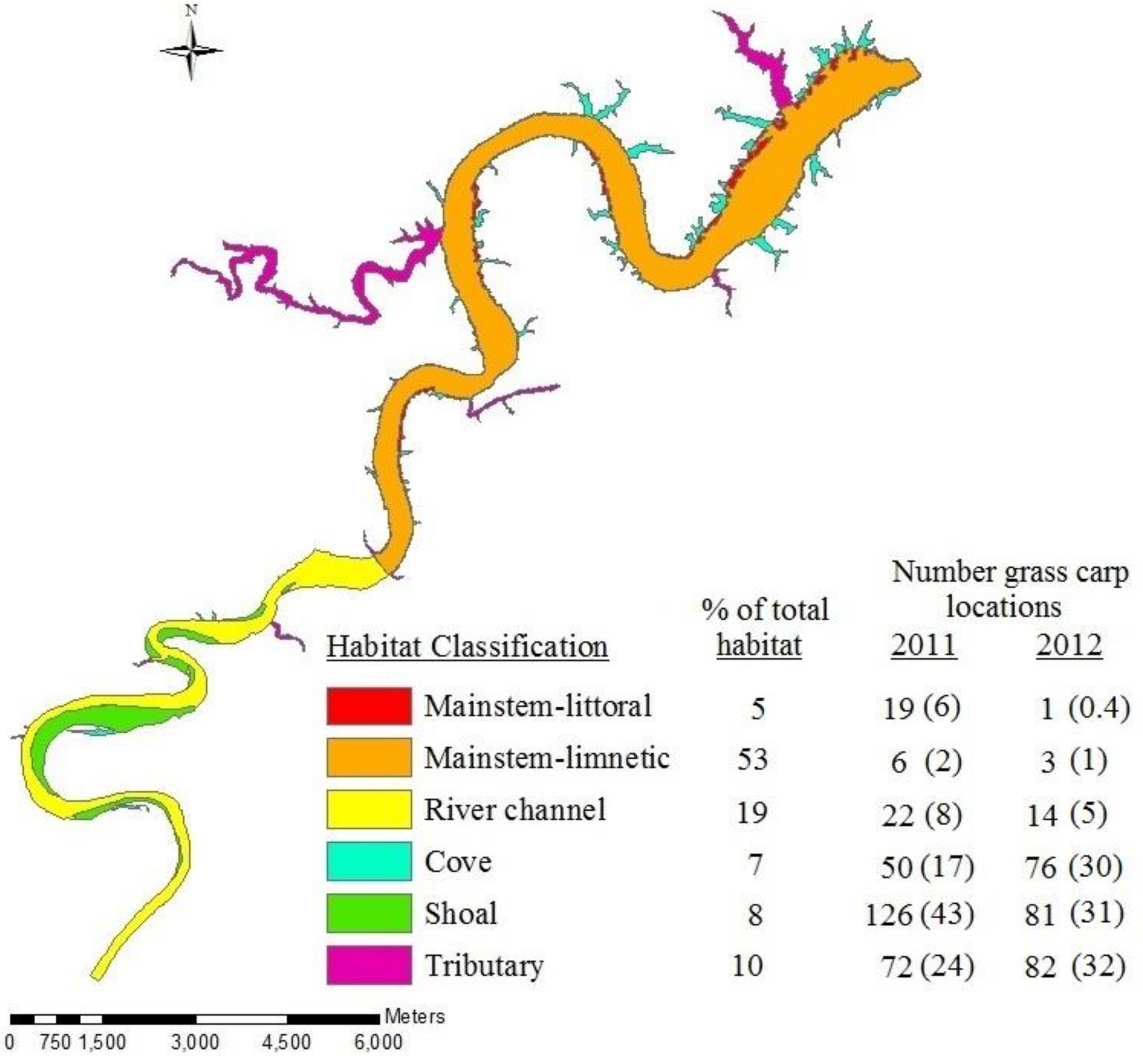
2011 Cohort				2012 Cohort			
Model Parameters	r^2	*p*	AICc	Model Parameters	r^2	*p*	AICc
PC1	0.32	0.004	73.48	PC1	0.96	<0.0001	12.96
PC1, PC4	0.47	0.001	70.26	PC1, PC3	0.96	<0.0001	17.52
PC1, PC4, PC3	0.55	0.001	69.65	PC1, PC2, PC3	0.96	<0.0001	23.79
PC1, PC2, PC3, PC4	0.60	0.001	70.26				

Table 2.4. Parameter estimates for the best regression models characterizing radio-tagged grass carp movement in Claytor Lake.

2011 Stocking cohort				2012 Stocking cohort			
Term	Estimate	*t*-Ratio	*p*	Term	Estimate	*t*-Ratio	*p*
Intercept	-2.229067	-12.74	<.0001	Intercept	-1.853563	-20.54	<.0001
PC1	0.2749872	3.77	0.0012	PC1	0.5013663	15.45	<.0001
PC3	-0.258424	-1.86	0.0771				
PC4	-0.420141	-2.61	0.0167				

Analysis of habitat use by radio-tagged grass carp

Calculated mean variances between actual fish locations and an equal number of random points within Claytor Lake were 2.63 km^2 and 0.31 km^2 for the 2011 and 2012 stocking cohorts, respectively. Results from the spatial test statistic module in FishTel 1.4 indicated the distribution of radio-tagged grass carp observations for both cohorts were nonrandom (p<0.0001). Spatial habitat classifications for Claytor Lake, and the number of grass carp locations observed within each habitat type, are presented in Figure 2.4. The maximum likelihood chi-square test for resource selection confirmed that radio-tagged grass carp in Claytor Lake selected for specific habitat types (χ^2=1188, p<0.0001). Based on observed selection ratios (*wi*), radio-tagged grass carp selected for shoal, cove, and tributary habitat while generally avoiding mainstem-limnetic and river channel habitat (Table 2.5).



	Habitat Classification	% of total habitat	Number grass carp locations 2011	Number grass carp locations 2012
🟥	Mainstem-littoral	5	19 (6)	1 (0.4)
🟧	Mainstem-limnetic	53	6 (2)	3 (1)
🟨	River channel	19	22 (8)	14 (5)
🟦	Cove	7	50 (17)	76 (30)
🟩	Shoal	8	126 (43)	81 (31)
🟪	Tributary	10	72 (24)	82 (32)

Figure 2.4. Habitat classification map for Claytor Lake, percent of total habitat represented by each habitat type, and the number of radio-tagged grass carp locations (percent of total locations in parentheses) observed for each habitat type, by stocking cohort.

Table 2.5. Habitat selection ratios (*wi*) for radio-tagged grass carp stocked in Claytor Lake where *wi* > 1 indicate habitat selection, and *wi* < 1 indicate avoidance.

Habitat Type	*wi*	Lower 95%CI	Upper 95% CI
River channel	0.35	0.219	0.482
Mainstem-limnetic	0.031	0.011	0.051
Mainstem-littoral	0.738	0	2.241
Tributary	2.842	1.91	3.773
Cove	3.508	1.142	5.874
Shoal	4.977	3.165	6.789

Analysis of grass carp survival

A total of 6 radio-tagged grass carp stocked in 2011, and 4 stocked in 2012 did not survive the first month post-stocking and thus were removed from the survival analysis. For both cohorts of grass carp, time-dependent survival ($S_{\text{time-dependent}}$) models received greater support than constant survival (S_{constant}) models based on AIC_c model weights (Table 2.6). The probability (95% CI) of grass carp stocked in 2011 surviving the first and second year in Claytor Lake was 0.44 (0.26, 0.63), and 0.55 (0.27, 0.80) respectively, whereas the probability of one-year survival for 2012 stocked fish was 0.25 (0.14, 0.40, Figure 2.5).

Table 2.6. Results of model selection from a known-fates survival analysis of grass carp stocked in Claytor Lake in 2011, and 2012 using AIC_c, and AIC model weights (w_i). *K* indicates the number of survival parameters estimated for each model.

Cohort	Survival Period	Model	AIC_c	ΔAIC_c	Akaike weight	*K*
2011	1st year	$S_{\text{time-dependent}}$	96.298	0	0.984	6
2011	1st year	S_{constant}	104.646	8.348	0.015	1
2011	2nd year	$S_{\text{time-dependent}}$	30.943	0	0.992	3
2011	2nd year	S_{constant}	40.552	9.608	0.008	1
2012	1st year	$S_{\text{time-dependent}}$	181.712	0	0.995	9
2012	1st year	S_{constant}	192.239	10.527	0.005	1

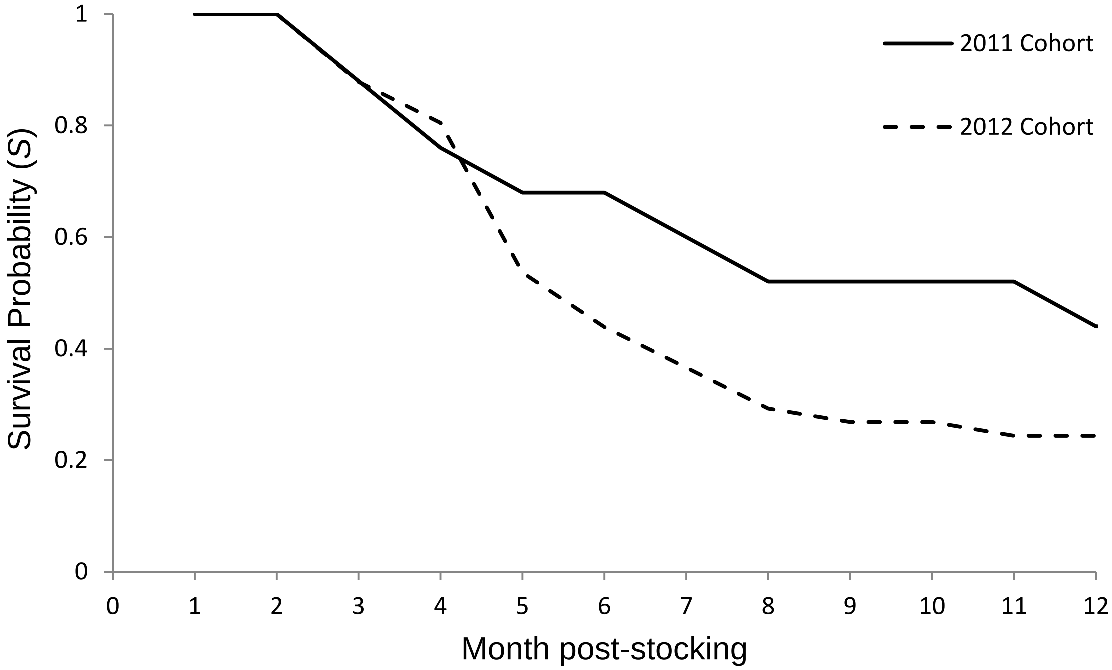


Figure 2.5. Estimated first-year survival of grass carp stocked in Claytor Lake in 2011, and 2012 based on time-dependent survival models generated from the known-fates analysis in program MARK. Radio-tagged grass carp that died within one month of release were removed from the analysis due to the likelihood that mortality was due to surgery-related complications, or tag loss.

Discussion

Grass carp movement patterns and habitat use in a riverine reservoir system

Our examination of grass carp movement patterns combined with hydrilla survey results and concurrent reductions in hydrilla biomass (Chapter 3) within Claytor Lake results suggest that grass carp can be effectively used to control hydrilla in a riverine reservoir. After acclimation, movements of Claytor Lake grass carp were highly localized primarily within areas hydrilla was documented. The range of total distance traveled (1.12-26.24 km) by grass carp over our 2-yr study generally falls within ranges identified in Florida (Nixon and Miller 1978;

Clapp et al. 1993), Alabama (Bain et al. 1990), and South Carolina (Kirk et al. 2001) studies of juvenile grass carp movement suggesting that the potential for long-range movements is not enhanced in a riverine reservoir setting. While post-stocking dispersal by radio-tagged grass carp occurred in an overall upstream pattern, only 3% of radio-tagged grass carp emigrated from Claytor Lake into the New River. Thus large-scale emigrations by newly stocked grass carp seem unlikely. Similarly, just four grass carp were sampled by VDGIF biologists in the New River upstream of Claytor Lake over the first two years of grass carp stocking (J.R. Copeland, VDGIF, personal communication). Whereas our study documented highly reduced movement after the initial month post-stocking, two studies have reported migrations ranging from 47 to 94 km by stocked grass carp in southeastern U.S. reservoirs (Bain et al. 1990; Maceina et al. 1999). For each of these studies, larger grass carp (>2kg) were tagged than those used in the Claytor Lake study, possibly indicating that as grass carp increase in age and size there is greater potential for migration (Bain et al. 1990; Chilton and Poarch 1997). Similar findings have been reported by Fischer and Lyakhnovic (1973) for grass carp in their native range as they approach maturity; thus it is possible that longer-range movements may occur as Claytor Lake grass carp age. Incidentally, VDGIF biologists sampled 32 grass carp (mean TL 716 mm) in electrofishing assessments of the New River upstream of Claytor Lake during spring and early summer 2013 (J.R. Copeland, VDGIF, unpublished data). However, during this period the New River was subject to high flows, and 27 of the grass carp collected in 2013 were captured within close proximity of Allisonia. Hence the increase in grass carp collections may be a result of high flows creating more-accessible habitat as opposed to increases in migration tendency. Another factor that may dictate the overall migration potential for grass carp is the abundance of preferred forage such as hydrilla. In 2011, lush stands of hydrilla were present in relatively close proximity to stocking locations in Claytor Lake. By summer 2012 hydrilla coverage and density was dramatically reduced throughout Claytor Lake which coincided with the first observed emigrations by grass carp into the New River. Similarly, Clapp et al. (1993) documented significantly greater movements by grass carp within a sparsely vegetated reservoir when compared to movements by grass carp in a densely vegetated reservoir. While we did not document significant differences in monthly movement between 2011 and 2012, the combination of reduced forage and the approaching maturity of the grass carp may influence movement and migration rates in the future. Thus continued monitoring of grass carp beyond our study period may be required to gain a more-complete understanding of their long-term migration potential in Claytor Lake.

Through regression, we identified significant correlations between grass carp movement patterns in Claytor Lake and variations in temperature-, atmospheric-, age-, and habitat-related variables (including hydrilla presence). Temperature-related variables were positively correlated with grass carp movement and explained the greatest proportion of variation for both stocking cohorts which complements conclusions from previous studies regarding grass carp movement (Nixon and Miller 1978; Bain et al. 1990; Chilton and Poarch 1997). Interestingly, weather-related variables such as barometric pressure and wind speed were significant predictors of movement for the 2011 stocking cohort, but not the 2012 stocking cohort. These findings may indicate that as grass carp age, finer-scale weather conditions have a greater influence on grass carp movement. The influence of flow-related variables on fish species is well documented at various temporal and spatial scales (Taylor and Cooke 2012). Within their native range, concurrent increases in streamflow and temperature are believed to cue long-range, upstream migrations of grass carp presumably for reproduction (Shireman and Smith 1983). Contrary to findings by Prentice et al. (1998), we did not observe significant relationships between flow-related variables and grass carp movement for either stocking cohort. It is possible that more-temperate conditions in reservoirs such as Claytor Lake override flow-related movement tendencies for grass carp. Historically, peak annual flows measured at the Allisonia USGS gauging station often occur between December and February. During this period ambient water temperatures are generally the lowest observed annually (range 3-8º C in 2012-2013), and subsequently fall below previously identified temperature thresholds for grass carp activity (Stroganov 1963; Wiley and Wike 1986; Chilton and Muoneke 1992). Therefore, variations in movement patterns of stocked juvenile grass carp in more northerly waterbodies appear to be more climate-dependent than in lower lattitudes.

Claytor Lake grass carp selected for habitats colonized by hydrilla further supporting their efficacy as a biological control agent in this system, and possibly similar reservoirs. Prior hydrilla coverage surveys in Claytor Lake found that shoal habitat accounted for 75% of the total hydrilla coverage. Accordingly, radio-tagged grass carp demonstrated the highest selection ratios for shoal habitat suggesting that hydrilla abundance is likely a primary factor in grass carp habitat selection. Prior grass carp investigations have suggested grass carp show an affinity for vegetated areas by grass carp stocked into a new system (Mitzner 1978; Nixon and Miller 1978; Bain et al. 1990; Clapp et al. 1993; Kirk et al. 2001); however, habitat selection by grass carp has previously not been quantified whereas our study confirmed selection for habitat colonized by hydrilla. Claytor Lake grass carp also selected cove and tributary habitats for which we also documented hydrilla coverage, although the degree of hydrilla coverage was generally lower than that of shoal habitats. However, several radio-tagged grass carp moved into apparently non-vegetated tributary and cove habitats shortly after stocking, and remained there for the duration of the study. Thus it is possible that fine-scale habitat characteristics such as structure, substrate, depth, and thermal conditions may also be important factors for grass carp habitat selection. For example, radio-tagged grass carp were often located in close proximity to complex habitat such as docks, felled trees, and beaver lodges in the absence of hydrilla. Additionally, cove and tributary habitats utilized by numerous radio-tagged grass carp primarily consisted of silt and muck substrates often mixed with large amounts of organic matter. While such fine-scale habitat measurements were beyond the scale of our investigation, our observations support previous evidence of grass carp homing to highly specific areas within a waterbody (Mitzner 1978). Overall, vegetation abundance appears to guide grass carp habitat selection in Claytor Lake. Additionally, our documentation of grass carp selection of non-vegetated cove and tributary habitats may benefit managers in targeting grass carp sampling efforts for population dynamics investigations, or removal efforts from systems where grass carp stocking has led to undesirable results.

First-year survival of stocked grass carp

Our examination of grass carp survival in Claytor Lake revealed considerably lower survival rates than reported for other large reservoirs in the USA, suggesting that annual survival rates of grass carp are variable among systems. For example, annual survival rates ranged from 61-80% in Santee-Cooper Reservoir, South Carolina (Kirk et al. 2000). In Lake Gaston, Virginia-North Carolina annual survival rates for grass carp were 75-80%, although first-year survival of Lake Gaston grass carp was just 53% using age-structured methods (Stich et al. 2013). The comparatively low first-year survival rates observed for Claytor Lake grass carp may be explained by a combination of factors including size-at-stocking, predator density, and vegetation abundance. The 2012 stocking cohort was significantly smaller and had lower survival rates (mean TL 394 mm, 25% survival) than the 2011 stocking cohort (mean TL 494 mm, 44% survival). Accordingly, numerous studies have reported greater survival by larger stocked grass carp presumably due to decreased vulnerability to predation by piscivores (Shireman et al. 1978; Hill 1986; Clapp et al. 1993). Shireman et al. (1978) suggested grass carp less than 410 mm TL are vulnerable to predation by 600 mm TL largemouth bass based on body size and gape measurements. Grass carp from both stocking cohorts were generally large enough to avoid significant largemouth bass predation, however, the habitats selected by Claytor Lake grass carp (shoals, coves, tributaries) may overlap with large-gaped piscivorous fishes present in the system such as striped bass *Marone saxatilis*, flathead catfish *Pylodictus olivarus*, and muskellunge *Esox masquinongy*. Avian piscivores such as osprey *Pandion haliaetus*, bald eagles *Haliaeetus leucocephalus*, and great blue herons *Ardea herodias* may also impact the survival rates of Claytor Lake grass carp. Little is currently known about the predation potential of these species on stocked grass carp populations in reservoir environments, although they were commonly sighted near shallow shoal areas where tagged grass carp consistently congregated. Similarly, mammalian piscivores such as otters *Lontra canadensis*, mink *Mustela vison*, and raccoons *Procyon lotor* were commonly sighted along the shoreline adjacent to shoal and cove habitats in Claytor Lake. A study by Adámek et al. (2003) found that otters preyed upon grass carp up to 600 mm TL, and 2.7 kg in fish production ponds. Coincidentally, many of the "dead" tags in the present study were found highly clustered within localized areas of shoal and cove habitats suggesting predation by piscivorous birds and mammals may have been a significant source of mortality for both stocking cohorts. Another factor that may explain lower survival of Claytor Lake grass carp is limited vegetation, which supplies both forage and refugia. Prior studies on grass carp survival were conducted in large reservoirs with relatively abundant levels of hydrilla throughout the study periods (Kirk et al. 2000; Stitch et al. 2013). In Claytor Lake significant reductions of hydrilla coverage occurred in 2012 subsequently removing refugia in shallow habitats and also reducing the primary food source for grass carp. Thus, reduced hydrilla coverage may further explain reduced survival by the 2012 stocking cohort, and suggests that first-year grass carp survival may remain low for future stocking cohorts. Understanding survival rates of stocked grass carp is a critical component for incremental stocking designs. Managers can use survival estimates to directly assess triploid grass carp population size because stocking numbers are presumably known and no reproduction occurs, thus allowing for adaptive stocking approaches to maintain ideal densities of grass carp. By using radio-telemetry to estimate initial survival of grass carp stocked into a new system we identified lower survival rates than previously documented in large U.S. reservoirs. These findings provide greater insight into future management for Claytor Lake and similar systems, and also suggest that grass carp survival can be highly site-specific and should be evaluated when incremental stocking strategies are employed to aid in achieving desired results.

Management implications and future research

Since its introduction into Florida waters around 1960 hydrilla has spread widely throughout the United States, including as far north as Maine and Washington (Blackburn et al. 1969; Langeland 1996; Shabana et al. 2003). However, investigations of grass carp use to control hydrilla in more-temperate regions of the U.S. are limited. Thus our examination of grass carp movement patterns, habitat use, and annual survival provides an important case study for future management in similar waterbodies. For example, hydrilla has been documented across Virginia including infestations in at least seven reservoirs (J.R. Copeland, VDGIF, personal communication). Overall, our findings suggest that juvenile grass carp are effective for managing hydrilla in more-temperate riverine reservoirs like Claytor Lake. However, hydrilla management using incremental grass carp stockings is generally a long-term endeavor. Therefore, research focused on grass carp behavior and survival in reservoir environments after hydrilla has been dramatically reduced is needed to understand the long-term efficacy of grass carp management. We documented minimal migration by age 1-2 grass carp during our study; although, the current literature combined with more-recent grass carp collections in the New River indicate that migration potential may increase as grass carp age. Hence, an examination of mature grass carp movement in both reservoir and lotic ecosystems could benefit future management strategies, or grass carp removal efforts in cases where non-target vegetation is impacted. Grass carp survival in Claytor Lake was lower than previous reports which we speculate was related to a high diversity of predator species and reductions in hydrilla abundance. A greater understanding of grass carp vulnerability to avian and mammalian predators could provide important insight into ideal stocking sizes which minimizes grass carp predation, or conversely provide managers with an expected mortality rate due to predation that could be incorporated into stocking programs. Additionally, continued monitoring of grass carp survival should remain a priority over the long-term, thereby allowing managers to further evaluate the effects of stocking densities and grass carp population size on hydrilla within large reservoirs.

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Chapter 3: Examination of grass carp and hydrilla dynamics to guide future management in an Appalachian reservoir

Abstract

Hydrilla *Hydrilla verticallata* management efforts in large reservoirs of the United States often utilize triploid grass carp *Ctenopharyngodon idella* with a goal of achieving intermediate levels of hydrilla control. The success of long-term hydrilla management efforts in a moderately infested system such as Claytor Lake, Virginia could be improved by a greater understanding of grass carp and hydrilla dynamics early in the management process. Here, we examine grass carp population dynamics in conjunction with hydrilla growth dynamics in the development of a dynamic stocking model to aid long-term hydrilla management actions in Claytor Lake. Grass carp were initially stocked into Claytor Lake during spring 2011 and maintained at a density of approximately 37 fish per vegetated ha through subsequent annual stocking. Grass carp growth rates were rapid in 2011 and production reached 6.07 kg ha^{-1}, whereas in 2012 growth rates and production (1.93 kg ha^{-1}) declined substantially concurrent with significant reductions in hydrilla abundance. Our stocking model predicted variable levels of hydrilla control when alternative scenarios of grass carp growth and mortality were simulated, with fast growth and low-average mortality rates leading to hydrilla eradication by 2013. Conversely, a scenario of slow grass carp growth and high mortality rates predicted that hydrilla would be controlled without eradication through 2030 by maintaining approximately 5-6 metric tons of grass carp biomass within Claytor Lake. These findings suggest that grass carp growth potential is highly dependent upon vegetation abundance within a system, and that lower stocking densities may be adequate for hydrilla control in temperate climates. Our stocking-model simulations indicate that grass carp population dynamics can significantly influence the accuracy of long-term hydrilla management

efforts. Thus, detailed characterization of grass carp population dynamics should remain a focal point for achieving greater precision in hydrilla management efforts.

Introduction

Hydrilla *Hydrilla verticillata* can be considered one of the most troublesome exotic aquatic weeds present in U.S. waterbodies (Langeland 1996). Since introduction in the 1960s following releases from aquaria in Florida (Blackburn et al. 1969), hydrilla has been documented in at least 30 states as far north as Maine and Washington (EDDMapS 2013). Once established hydrilla infestations prove detrimental to industrial and recreational water uses and may require site-specific management approaches such as herbicide application, mechanical manipulation, or biological control (Langeland 1996; Madsen 1997).

The grass carp *Ctenopharyngodon idella* is an herbivorous fish native to East Asian and Pacific drainages (Fischer and Lyakhnovic 1973; Pipalova 2006) which was first imported to the United States in 1963 for its potential to control nuisance aquatic vegetation such as hydrilla. Since its introduction, the grass carp has been used widely by managers and researchers to control aquatic weeds with varying results (Bailey and Boyd 1972; Leslie et al. 1987; Cassani 1996). Production of triploid (sterile) grass carp in the 1980’s has permitted further introductions throughout the United States including large reservoir ecosystems (Cassani and Canton 1986; Allen and Wattendorf 1987; Bain 1993). In most cases the goal of hydrilla management in reservoirs is to achieve intermediate levels of hydrilla control while minimizing impact to non-target species. However, previous efforts utilizing a single, large-scale stocking event have often yielded undesirable results (either no perceivable control or complete eradication) due to uncertainty in appropriate stocking density (Noble et al. 1986; Leslie et al. 1996; Bonar et al. 2002). More recent efforts have utilized low-level, incremental grass carp stockings which allow for adaptive management of grass carp densities based on observed levels of hydrilla control (Bain 1993, Chilton and Magnelia 2008; Stich et al 2013).

Successful adaptive hydrilla management using grasss carp requires improved understanding of the relationships between carp and hydrilla production dynamics within ecosystems. However, a variety of challenges to this goal currently exist. For example, many of these variables (hydrilla production, grass carp population dynamics) are rarely characterized in the literature (Chilton and Muoneke 1992; Cassani 1995; Stich et al. 2013), let alone in the development of a dynamic model. Furthermore, management goals, stocking activities, and target plant species have varied widely in previous studies thereby limiting the applicability of any single study region-wide (Shireman and Maciena 1981; Sutton and Vandiver 1986; Blackwell and Murphy 1996; Bonar et al. 2002). Finally, grass carp consumption rates and seasonal plant growth are themselves highly dynamic variables influenced by a range of environmental conditions (Cassani 1995) further limiting comparability of recommendations among regions and waterbody types.

Several computer based simulation models have been developed to more accurately convey the complex relationships between grass carp and aquatic vegetation and to simulate the responses of the target vegetation to grass carp herbivory under a specified stocking density. However, such models may be of limited utility for managers considering long-term incremental stocking approaches to manage hydrilla because 1) the model was developed for regionally specific use (e.g., Wiley et al. 1987; Swanson and Bergersen 1988; Santha et al. 1991); or 2) the model only simulates a single stocking cohort over a 10-yr interval (e.g., Steward and Boyd 1999). Additionally, modeling long-term interactions between grass carp and hydrilla in a system requires knowledge of grass carp growth potential and survival.

Relatively few studies have addressed growth and mortality rates of stocked grass carp. Both of these metrics are believed to be influenced by grass carp density, climate, and vegetation abundance (Shelton et al. 1981; Chilton and Muoneke 1992). Grass carp grow rapidly in waterbodies with expansive hydrilla infestations (Shireman et al. 1980; Shireman and Maciena 1981; Morrow et al. 1997), whereas growth may be slowed and mortality rates increased in waterbodies with limited vegetation (Klussman et al. 1987; Morrow and Kirk 1995; Kirk et al. 2000; Manuel et al. 2013). Unfortunately, long-term growth and mortality rates of introduced grass carp populations have only been reported for systems where hydrilla infestations were initially expansive (Morrow et al. 1997; Stich et al. 2013). Currently, no studies have characterized long-term grass carp population characteristics in reservoirs with moderate hydrilla infestations. Therefore, an evaluation of grass carp and hydrilla dynamics early in the management process could allow for greater precision of long-term hydrilla management efforts within a moderately infested system such as Claytor Lake, Pulaski County, Virginia.

Hydrilla was first documented in Claytor Lake in 2003 and rapidly expanded its coverage to 162 ha by 2010. In 2011, the Virginia Department of Game and Inland Fisheries (VDGIF) approved the introduction of triploid grass carp to manage the rapidly expanding hydrilla infestation upon recommendation of the Claytor Lake Technical Advisory Committee (CLTAC). The long-term management goal identified by CLTAC for Claytor Lake is to reduce hydrilla coverage to approximately 40 ha and maintain this level of coverage by utilizing an incremental stocking approach. Therefore, we developed three primary objectives to inform future management actions: 1) to characterize grass carp growth and survival in Claytor Lake; 2) to examine seasonal grass carp herbivory on hydrilla and native aquatic plants in Claytor Lake; and

3) to develop a stocking model utilizing observed hydrilla-grass carp dynamics to estimate future stocking requirements to reach hydrilla coverage goals for Claytor Lake.

Methods

Study Site

Claytor Lake (Figure 3.1) is a 1,876-ha mainstream impoundment of the New River, located in the Valley and Ridge physiographic province. The reservoir is controlled by Appalachian Power, which generates electricity through a hydroelectric dam located on the northern end of the impoundment. The reservoir flows from southeast to northwest, is 34 km long, has a maximum width of 0.8 km, mean depth of 15 m, shoreline development index of 10.65, maximum normal pool elevation of 563 m above sea level, and an average retention time of approximately 33 days (Rosebery 1951). Claytor Lake is a public water source for Pulaski County, and provides a variety of water-based recreational activities for stakeholders including fishing, swimming, boating, and nature viewing (Appalachian Power 2009). Prior to the establishment of hydrilla, the diversity of submersed aquatic plants present within Claytor Lake was relatively low (J.R. Copeland, VDGIF, personal communication) with major vegetation beds localized in the shoal areas of upper Claytor Lake and several coves along the northwest shoreline in lower Claytor Lake. By 2010 hydrilla was the dominant aquatic plant in Claytor Lake, and was estimated to cover approximately 124 ha in the shoal areas of upper Claytor Lake and 38 ha across numerous coves and small tributaries near Claytor Lake State Park (Figure 3.1).

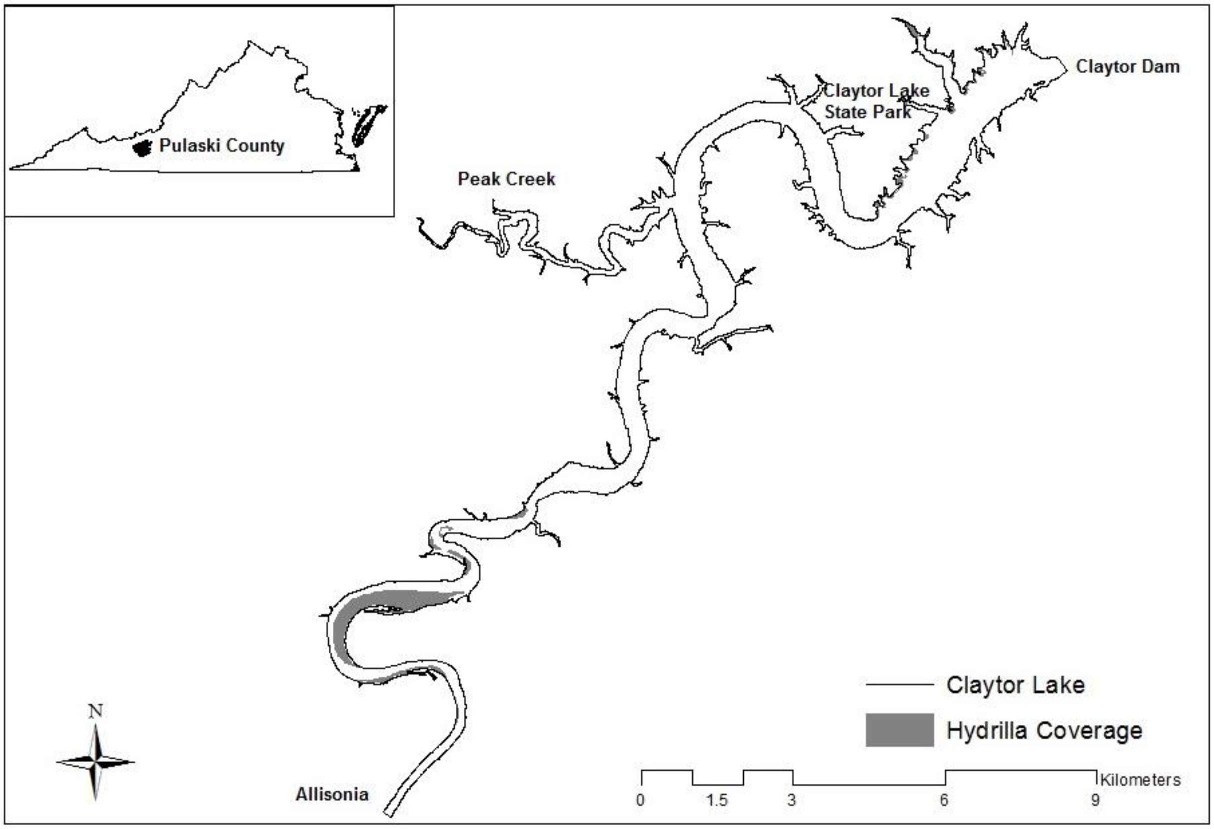

Figure 3.1. Map of Claytor Lake, Pulaski County, Virginia along with hydrilla coverage identified during a fall 2010 survey.

Analysis of grass carp population dynamics

Approximately 10,500 triploid grass carp were stocked into Claytor Lake over the duration of this study: 6,000 in 2011, 3,000 in 2012, and 1,500 in 2013. Based on a 2010 hydrilla coverage estimate of 162 ha, the initial stocking density of grass carp was approximately 37 fish per vegetated ha. Prior to stocking, we subsampled each cohort for total length (TL, mm) and weight (kg) to later enable estimation of secondary production over each growing season. Additionally, 1,000 grass carp stocked in 2012, and 600 grass carp stocked in 2013, were weighed and measured prior to receiving numbered anchor tags (Floy Tag and Mfg. Inc, Seattle, Washington) to enable precise growth assessment at future collection dates.

At the conclusion of each growing season, we utilized electrofishing, gill-netting, and bowfishing methods to sample grass carp from Claytor Lake. To determine age and stocking year we removed and processed the lapillar otoliths from all sampled grass carp using methods described by Morrow et al. (1997). Only grass carp stocked in 2011 and 2012 were included in the growth analysis described here. We calculated Fulton's condition factor for grass carp at each sampling period to assess changes in body condition using the equation:

$$K = \left(\frac{W}{L^3}\right) * 100{,}000$$

where K is condition, W is weight (g), L is length (mm), and 100,000 is a scaling constant (Anderson and Neumann 1996; Pope and Kruse 2007). Secondary production by each cohort was estimated using the instantaneous growth rate equation:

$$\hat{P} = \hat{G}\bar{B}$$

where $\hat{P}$ equals estimated secondary production for a given cohort within a specified interval, $\hat{G}$ equals estimated instantaneous growth rate for the cohort from time t to $t+1$, and $\bar{B}$ equals the estimated arithmetic mean cohort biomass from time t to $t+1$ (Ricker 1946; Allen 1949; Hayes et al. 2007). Population estimates for production calculations were derived from initial stocking numbers and annual mortality rates identified through an accompanying radio-telemetry study of stocked grass carp in Claytor Lake (Chapter 2).

Exclosure experiment

An exclosure experiment was completed over the 2012 growing season to estimate hydrilla herbivory by stocked grass carp, and to determine if grass carp would selectively feed on native vegetation. Seven exclosure sites were selected across Claytor Lake: four mixed native vegetation sites dominated by wild celery (*Vallisneria americana*) located within coves in the northwest portion of the lake and three monotypic hydrilla sites located within shallow mud flats in upper Claytor Lake. At each site, five randomly placed 1-m^2 exclosures were constructed during the winter of 2011 (1.8-m steel T-posts and 122-cm plastic construction fencing; Tenax Corporation, Baltimore, Maryland) along with three randomly placed 1-m^2 control plots (four T-posts without fencing). We visited each exclosure and control plot approximately monthly to photo-document potential changes throughout the growing season and monitor for potential breaches in the exclosure fencing. At the conclusion of the study (annual peak biomass) we manually removed all plant biomass from exclosures and controls. Samples were placed on ice and brought back to a lab for further processing. To determine fresh weight (FW), we spun each sample for 5 minutes using a 19-L industrial grade salad dryer (Global Equipment Co Inc., Port Washington, New York), weighed, and re-spun until a constant weight was reached. We tested for differences in plant biomass between controls and exclosures using analysis of variance (ANOVA, α=0.05).

Hydrilla-grass carp simulation model

We utilized the dynamic systems modeling program Vensim (Ventana Systems Inc., Harvard, Massachusetts) to simulate the dynamics between stocked grass carp and hydrilla in Claytor Lake, and to identify future grass carp stocking requirements to maintain desired levels of vegetation control. The model runs on a monthly time-step and is composed of two submodels: 1) a stage-based hydrilla submodel that simulates growth in hydrilla biomass throughout the growing season, and 2) an age-structured grass carp submodel that simulates grass carp herbivory on hydrilla throughout the growing season (Figure 3.2).

Hydrilla submodel

The submodel simulates hydrilla growth as a function of monthly water temperatures. Water temperature data was collected at 5 sites spanning the length of Claytor Lake during 2012-2013 using Hobo Pro V2 (Onset Computer Corporation, Bourne, Massachusetts) temperature loggers programmed to record measurements every four hours. We pooled all recorded water temperature from Claytor Lake and used the sine wave function in Vensim to determine the relationship between month of year and water temperature. Although hydrilla has multiple reproductive strategies, tubers are the primary source of hydrilla persistence in a previously infested system (Harlan et al. 1985). Therefore, in our model we assumed that annual growth of hydrilla is a function of subterranean tuber biomass. Sprouting of hydrilla tubers occurs in April when water temperatures reach 11-16º C (Harlan et al. 1985; Rybicki and Carter 2002). We assumed that tubers had a mortality rate of 0.0208 month^{-1} based on reports that propagules persist for approximately four years (Van and Steward 1990; Sutton 1996). We estimated that the annual sprout rate for hydrilla tubers was 7% of total tuber biomass assuming a tuber density of 500 m^{-2} and mean plant density of 35 plants m^{-2} (Bowes et al. 1979). In October tuber production occurs, which we hypothesized was approximately 9% of peak hydrilla biomass based on an average tuber weight of 0.00023 kg (Rybicki and Carter 2002; Bianchini et al. 2010). We used mean hydrilla biomass density observed within exclosures to estimate previous hydrilla biomass levels in Claytor Lake extrapolated to total spatial coverage. Using initial estimates of 16.2 ha of hydrilla coverage in 2003, we estimated the initial tuber biomass and instantaneous growth rate (r) required to reach 162 ha of hydrilla coverage in 2010 assuming logistic growth (Gotelli 1995). Hydrilla carrying capacity (k) for Claytor Lake was estimated using a bathymetric map to identify the maximum area suitable for hydrilla growth in Claytor Lake, and multiplying this by the maximum biomass level recorded during the exclosure experiment. Based on ambient water temperatures observed for Claytor Lake in 2012 senescence of above-ground biomass begins in November when water temperatures drop below 11° C; by December hydrilla has completely senesced in Claytor Lake.

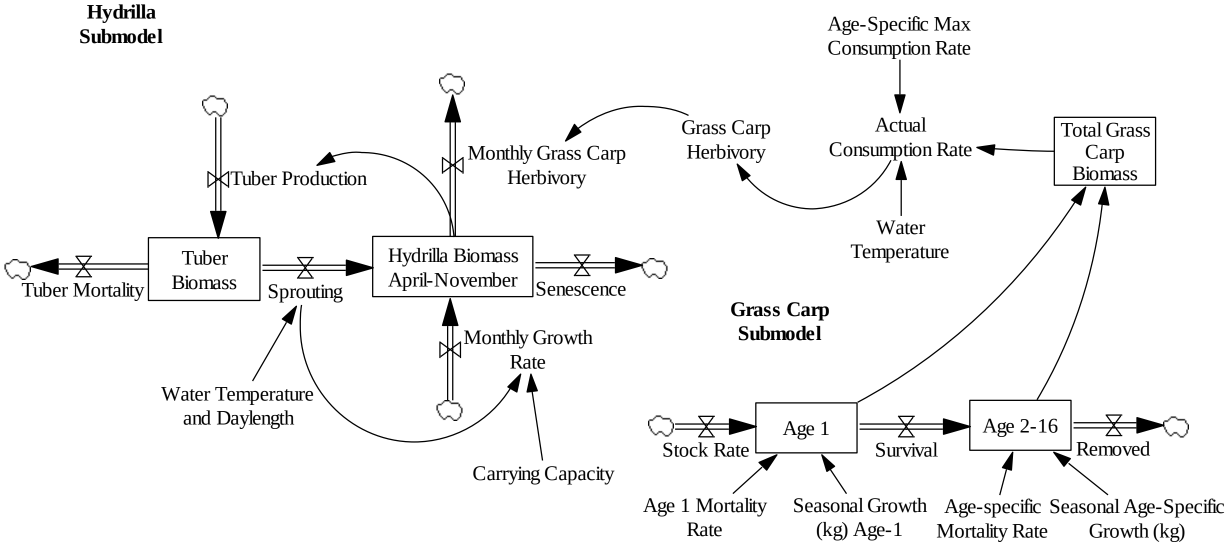

Figure 3.2. Conceptual model of stocked grass carp and hydrilla dynamics used to simulate hydrilla control by grass carp in Claytor Lake. Boxes in the submodels represent stocks (i.e. total hydrilla biomass, or number of grass carp), double-line arrows represent flows in or out of the respective systems, and single-line arrows are convertors.

Grass carp submodel

Maximum longevity reports for grass carp are variable in the literature; however Stich et al. (2013) found that grass carp up to 16 years of age contributed significantly to the overall level of grass carp biomass in Lake Gaston, Virginia-North Carolina. Thus, the grass carp submodel simulates grass carp growth, mortality, and herbivory through age 16, and fish are subsequently removed from the model thereafter. Grass carp enter the model at stocking in May and progress to the next age class the following May. We assumed that seasonal weight increases by grass carp were exponential, with growth occurring only when hydrilla is present in the system. We modeled grass carp herbivory as a temperature-dependent function of average grass-carp body weight (BW) using the equation:

$$C = -2.8591 + 1.19889\ log_e T$$

where C is the proportion of maximum daily consumption rate (% BW day^{-1}), and T is ambient water temperature (Wiley and Wike 1986). Changes in consumption rates as grass carp grow were simulated using the equation:

$$C = -29.02\ log_e W + 59.74$$

where C is daily consumption rate (% BW day^{-1}) and W is grass carp weight, based on findings by Osborne and Riddle (1999). We also assumed that no grass carp herbivory occurred at water temperatures below 11° C (Wiley and Wike 1986). To simulate hydrilla control by grass carp the submodel sums grass carp herbivory based on total grass carp biomass, and removes the consumed hydrilla biomass on a monthly basis from the hydrilla growth submodel.

Model evaluation

Growth and mortality rates of Claytor Lake grass carp beyond 2013 are currently unknown. We developed three separate submodels initialized with alternative grass carp growth and mortality rates to evaluate how variations in these factors would affect hydrilla control and future grass carp stocking requirements. The first model (M_c) utilizes current growth and mortality data observed for Claytor Lake grass carp. We used mean length-at-age data for sampled grass carp to estimate von Bertalanffy growth parameters with the equation:

$$L_t = L_\infty(1 - e^{-K(t-t_0)})$$

where $L\infty$ is the asymptotic length (mm), K is the growth coefficient, and t_0 is the theoretical age-0 length (von Bertalanffy 1938; Isley and Grabowski 2007). Parameter estimates were then used to project grass carp growth in length to age 16. We developed a weight-length relationship for sampled Claytor Lake grass carp using the formula:

$$W = aL^b$$

where W is weight, L is length, and a and b are estimated constants (Isley and Grabowski 2007). We then used length-at-age estimates to project mean weight-at-age to age 16. Mortality estimates determined through a concurrent telemetry study of Claytor Lake grass carp were used for age-1 and age-2 (Chapter 2). We assumed that annual mortality is reduced as grass carp increase in size, and therefore used age-specific mortality rates identified by Stich et al. (2013) for ages 3-16. Overall, M_c represents a scenario with low long-term growth potential and high initial mortality rates. For the two remaining scenarios, we utilized von Bertalanffy growth parameters and mortality rates reported for Santee-Cooper Reservoir, South Carolina (M_{sc}; Morrow et al. 1997), and Lake Gaston, Virginia-North Carolina (M_g; Stich et al. 2013). M_{sc} was representative of a grass carp population with high growth and low mortality rates, whereas M_g represented more-linear grass carp growth rates, and average mortality rates.

We simulated each model using the initial stocking regime of 6,000, 3,000, and 1,500 grass carp released in 2011, 2012, and 2013 in Claytor Lake, respectively. We assumed that stocking grass carp into Claytor Lake would prevent future expansion of hydrilla coverage, and therefore we used the 2010 hydrilla coverage estimate of 162 ha as a reference for determining annual reductions in hydrilla density (kg m^{-2}). Based on the level of hydrilla control predicted by each model, we examined future stocking regimes and grass carp biomass levels required to maintain desired levels of hydrilla control in Claytor Lake through the year 2030.

Results

Analysis of grass carp population dynamics

We collected 29 grass carp after the 2011 growing season and 54 at the conclusion of the 2012 growing season for a total of 83 collected grass carp. Electrofishing was the most successful collection method (n=80). The mean length- and weight-at-age for sampled cohorts of grass carp is shown in Table 3.1, where age-1 indicates size-at-stocking. Additionally, seven floy-tagged fish stocked in 2012 were collected in the fall 2012 sample with a mean length and weight of 530 mm and 1.78 kg, respectively, which was analogous to growth observed for non-tagged grass carp from the 2012 stocking. We found that grass carp condition followed a similar pattern of increase in 2011 followed by a decrease in condition for three of the four size-groups sampled in 2012 (Table 3.2). Grass carp production in Claytor Lake over the 2011 growing season was 6.07 kg ha^{-1}, whereas production over the 2012 growing season declined to 1.93 kg ha^{-1} (Table 3.3).

Table 3.1. Mean length- and weight-at-age (±SE) for grass carp stocked in 2011 and 2012 in Claytor Lake.

	Mean length (mm)			Mean weight (kg)		
Stocking-year	Age-1	Age-2	Age-3	Age-1	Age-2	Age-3
2011	394 (5)	618 (11)	717 (11)	0.60 (0.02)	3.51 (0.17)	4.65 (0.32)
2012	334 (4)	531 (8)	-	0.42 (0.02)	1.88 (0.09)	-

Table 3.2. Calculated condition factors (K) for specified size-groups of Claytor Lake grass carp sampled prior to stocking and after subsequent growing seasons.

	K		
Length (mm)	Stocking	Fall 2011	Fall 2012
200-299	1.12		
300-399	1.03		
400-499	0.98	1.48	1.14
500-599		1.21	1.22
600-699		1.43	1.15
700-799		1.40	1.32

Table 3.3. Estimated instantaneous growth rates (G), biomass ($\bar{B}$), and production (P) of Claytor Lake grass carp over the 2011 and 2012 growing seasons.

	2011			2012		
Age	G	$\bar{B}$	P	G	$\bar{B}$	P
2	1.76	6469	11381	1.47	1354	1991
3	-	-	-	0.21	7800	1626
Total (kg)		6469	11381		9153	3617
Total P (kg ha^{-1})		3.45	6.07		4.88	1.93
$P/\bar{B}$		1.76			0.40	

Exclosure Experiment

Control and exclosure plots at both native vegetation and hydrilla sites were harvested in late September 2012. Despite effective exclusion of grass carp for a majority of the growing season at native exclosure sites, all native plant exclosures were compromised and biomass levels were greatly reduced within two weeks of the expected harvest date, thus precluding biomass comparisons. However, monthly monitoring of the native plant exclosures showed that all vegetation readily accessible to grass carp was eradicated early in the growing season indicating that grass carp will target native vegetation in Claytor Lake. Two of the hydrilla exclosures were damaged by large, floating trees during spring 2012; thus they were removed from the biomass comparison. None of the remaining hydrilla exclosures showed signs of being compromised prior to harvest. Mean FW of hydrilla biomass harvested within the exclosure and control plots are shown in Table 3.4. Results from ANOVA found that hydrilla biomass was significantly lower in control plots compared to the exclosures (p<0.0001), indicating that on average grass carp herbivory reduced hydrilla biomass by 1.19 kg m^{-2} at exclosure sites in Claytor Lake over the 2012 growing season.

Table 3.4. Results from the hydrilla exclosure experiment conducted over the 2012 growing season in Claytor Lake. Hydrilla biomass levels (kg FW) were significantly lower in control plots compared with exclosure plots (p<0.0001).

Plot type	n	Mean depth (m)	Mean biomass (kg m^{-2})	SE	Range (kg m^{-2})
Control	9	0.84	0.06	0.01	0-0.11
Exclosure	13	0.77	1.25	0.18	0.59-2.81

Hydrilla-grass carp simulation model

Estimated parameters used in the hydrilla submodel are presented in Table 3.4. Overall, the model accurately portrayed annual hydrilla biomass expansion within Claytor Lake using a hydrilla density of 1.25 kg m^{-2} extrapolated to total hydrilla coverage estimates of 16 and 162 ha identified during 2003 and 2010, respectively (Figure 3.3). With no grass carp stocking, the hydrilla submodel predicts a carrying capacity of 1,492 metric tons of hydrilla biomass, and 533 ha of hydrilla coverage by the year 2022 in Claytor Lake.

Estimates of von Bertalanffy growth parameters, and weight-length parameters derived from Claytor Lake grass carp data (M_c), along with parameter estimates reported for Santee-Cooper Reservoir (M_{sc}) and Lake Gaston (M_g), are presented in Table 3.6. Overall, predicted somatic growth for M_c and M_{sc} is greater at early ages than M_g. However, the more-linear trajectory of M_g predicts significant annual weight increases through age 16, whereas both M_c and M_{sc} predict that grass carp will reach asymptotic weight at approximately age 10 (Table 3.7)

Simulations of the hydrilla-grass carp model using the initial 3-yr stocking regime predicted moderate reductions of hydrilla biomass in 2011 for all grass carp submodels; however, M_g predicted eradication of hydrilla biomass by 2012, and M_{sc} predicted eradication by 2013 (Table 3.8). Predicted grass carp biomass peaked in 2013 for each model with M_{sc} reaching over 64 metric tons, whereas M_c and M_g predicted grass carp biomass levels that were considerably lower at approximately 11 and 17 metric tons, respectively. Although M_{sc} and M_g predicted hydrilla eradication by 2013 we simulated each model through 2030 with no additional grass carp stocking and found that grass carp biomass levels remained high enough to prevent hydrilla recovery within this time period. Our simulations of future stocking regimes for M_c predicted that an annual stocking of 666 grass carp, or approximately 320 kg, will maintain a peak hydrilla biomass level of approximately 500 metric tons (or 40 ha of hydrilla coverage at a density of 1.25 kg m^{-2}) through the year 2030 in Claytor Lake (Figure 3.5). Simulations of M_c using an alternate-year stocking interval required 1,650 (792 kg) grass carp to maintain hydrilla control, whereas 3-yr, and 4-yr stocking intervals required 3,100 (1488 kg) and 5,200 (2,496 kg) grass carp, respectively (Table 3.9).

Table 3.5. Parameter estimates for tuber death rate (*Z*), tuber production rate (*P*), initial tuber biomass, hydrilla growth rate (*r*), carrying capacity (*k*), and mean hydrilla density used in the hydrilla submodel to simulate seasonal hydrilla dynamics in Claytor Lake.

Tuber *Z*	Tuber P	Tuber Biomass (kg)	Hydrilla *r*	Hydrilla *k* (kg)	Density (kg m^{-2})
0.0208	0.09	15,000	0.055	1,492,000	1.25

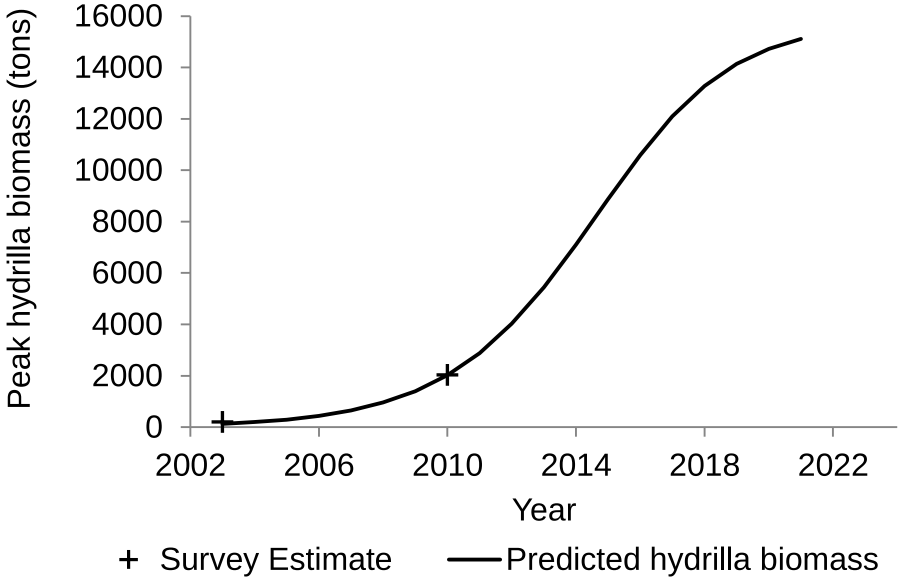

Figure 3.3. Annual peak hydrilla biomass levels predicted by the hydrilla submodel, compared with hydrilla coverage survey estimates converted to biomass assuming a hydrilla density of 1.25 kg m^{-2}. Overall the model accurately portrayed hydrilla expansion between 2003 and 2010, and predicts that peak hydrilla biomass levels will reach carrying capacity by 2022 in Claytor Lake without grass carp management.

Table 3.6. Estimated von Bertalanffy growth parameters and weight-length parameters derived from Claytor Lake grass carp data (M_c) compared with reported grass carp growth parameters for Santee-Cooper Reservoir, South Carolina (M_{sc}) and Lake Gaston, Virginia-North Carolina (M_g).

	VBGF Parameters			W-L Parameters	
Model	$L\infty$	t_0	k	a	b
M_c	791	0.115	0.650	2.82E-06	3.24
M_{sc}	1044	0.590	0.615	4.25E-06	3.19
Mg	1297	-1.520	0.135	3.25E-05	2.87

Table 3.7. Projected length- and weight-at-age, along with instantaneous mortality rates (Z) for grass carp used in submodels M_c, M_{sc}, and M_g to simulate hydrilla control by grass carp in Claytor Lake.

	M_C			M_{SC}			M_G		
Age	Length (mm)	Weight (kg)	Z	Length (mm)	Weight (kg)	Z	Length (mm)	Weight (kg)	Z
1	346.1	0.47	0.087	232.7	0.15	0.017	374.5	0.79	0.039
2	559.0	2.21	0.036	605.4	3.08	0.017	491.1	1.72	0.03
3	670.1	3.97	0.025	806.9	7.7	0.017	593.1	2.96	0.025
4	728.1	5.2	0.019	915.8	11.53	0.017	682.1	4.42	0.019
5	758.3	5.93	0.022	974.7	14.06	0.017	759.8	6.02	0.022
6	774.1	6.34	0.018	1006.5	15.57	0.017	827.8	7.7	0.018
7	782.4	6.56	0.017	1023.7	16.44	0.017	887.1	9.39	0.017
8	786.7	6.68	0.016	1033.1	16.92	0.017	938.9	11.05	0.016
9	788.9	6.74	0.015	1038.1	17.18	0.017	984.2	12.65	0.015
10	790.1	6.77	0.014	1040.8	17.33	0.017	1023.8	14.16	0.014
11	790.7	6.79	0.014	1042.3	17.4	0.017	1058.3	15.58	0.014
12	791.0	6.8	0.013	1043.1	17.45	0.017	1088.5	16.89	0.013
13	791.2	6.8	0.013	1043.5	17.47	0.017	1114.9	18.09	0.013
14	791.3	6.8	0.013	1043.7	17.48	0.017	1137.9	19.18	0.013
15	791.3	6.81	0.013	1043.9	17.49	0.017	1158.0	20.17	0.013
16	791.3	6.81	0.013	1043.9	17.49	0.017	1175.6	21.06	0.013

Table 3.8. Predicted peak grass carp and hydrilla biomass (*B*, metric tons) and hydrilla density (*D*, kg m^{-2}) between 2011 and 2013 derived from simulations of M_c, M_{sc}, and M_g using the 2011-2013 grass carp stocking regime for Claytor Lake.

	M_c			M_{sc}			M_g		
Year	Grass Carp *B*	Hydrilla *B*	*D*	Grass Carp *B*	Hydrilla *B*	*D*	Grass Carp *B*	Hydrilla B	*D*
2011	8.33	952.57	0.59	17.01	2016.63	1.24	8.45	856.96	0.53
2012	10.68	637.16	0.39	43.21	310.73	0.19	13.65	0	0
2013	11.15	434.12	0.27	64.04	0	0	16.85	0	0

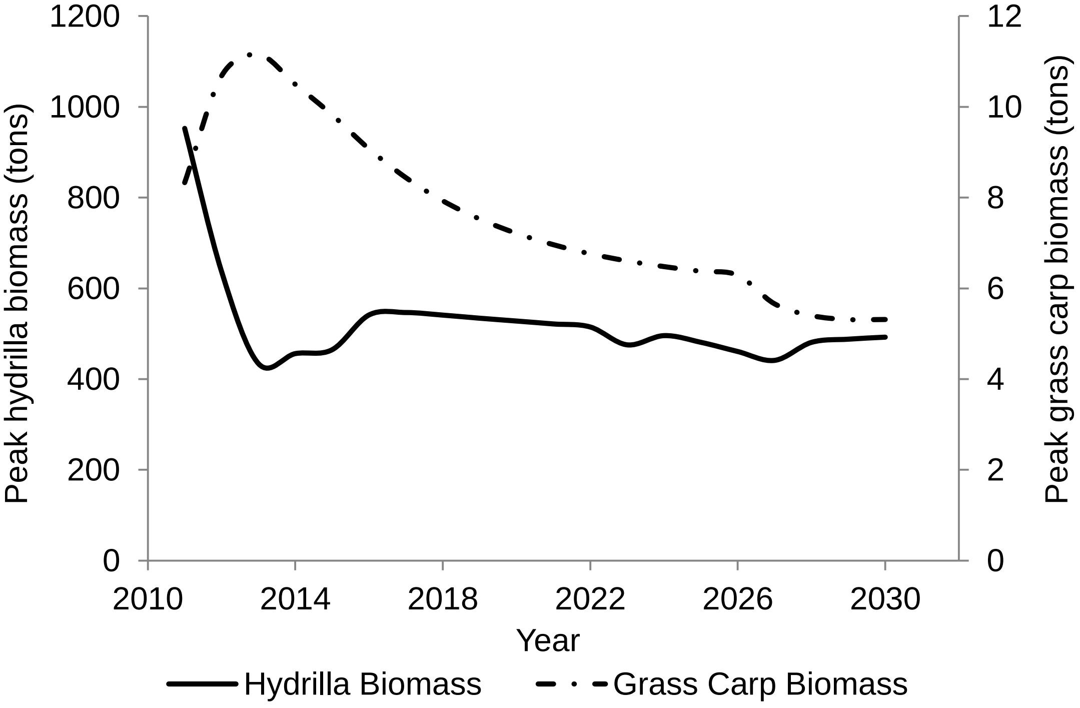

Figure 3.4. Predicted peak hydrilla and grass carp biomass in Claytor Lake for 2011-2030 under grass carp dynamics used in M_c. The model predicts that a stocking rate of approximately 320 kg of grass carp annually is required to maintain peak hydrilla biomass at approximately 500 metric tons (40 ha of hydrilla coverage at a density of 1.25 kg m^{-2}).

Table 3.9. A comparison of the number of grass carp required at 1-,2-,3-, or 4-yr stocking intervals to maintain hydrilla control in Claytor Lake using simulations from M_c through 2030.

Stocking interval	Stocking requirement	Number of stockings	Total stocked (thru 2030)	Hydrilla biomass range (metric tons)
1-yr	666	16	10,656	403-502
2-yr	1,650	8	13,200	500-729
3-yr	3,100	5	18,600	402-1033
4-yr	5,200	4	21,200	500-1500

Discussion

Our examination of the dynamics between hydrilla and grass carp in Claytor Lake revealed several important insights regarding hydrilla management in large reservoirs with intermediate hydrilla infestations. Over the 2011 growing season we observed grass carp growth rates comparable to reports from Florida (Shireman et al. 1980), Texas (Klussman et al. 1987), Alabama (Morrow and Kirk 1995), and South Carolina (Morrow et al. 1997) waterbodies despite overall shorter growing seasons and annual senescence of aquatic vegetation in Claytor Lake. Conversely, grass carp sampled in fall 2012 exhibited reductions in annual growth rates, condition, and overall production concurrent with significant declines in hydrilla abundance. Thus it appears that vegetation abundance is likely the primary factor influencing changes in grass carp growth and associated metrics. Our simulations of hydrilla and grass carp dynamics in Claytor Lake predicted hydrilla would either be eradicated by 2012 (M_g, linear growth, average mortality), 2013 (M_{sc}, high growth, low mortality), or be suppressed by approximately 80% of its potential by 2013 (M_c, low growth, high mortality). Accordingly, both M_g and M_{sc} predicted grass carp standing stocks would remain high enough to prevent re-growth of hydrilla through 2030, whereas M_c predicted that a grass carp standing stock of approximately 5 to 6 metric tons would suppress hydrilla biomass to 500 metric tons. The following discussion will examine the implications that these results have for future grass carp-hydrilla management in Claytor Lake and similar reservoir environments.

Evaluation of hydrilla-grass carp dynamics model

Our simulations of grass carp-hydrilla dynamics in Claytor Lake demonstrated the significant influence of grass carp growth and mortality on long-term hydrilla management efforts using an incremental stocking approach. Thus it is important to address the validity of these results for guiding future grass carp stocking strategies in Claytor Lake. Further investigation into these model predictions suggests that the transferability of grass carp dynamics between extensively infested and moderately infested waterbodies may be limited after hydrilla is controlled. While our exclosure experiment documented near eradication of hydrilla at exclosure sites in 2012 (mean density 0.06 kg m^{-2}) approximately 1-m deep, we also observed greater hydrilla biomass density in deeper habitats during alternative field observations. Therefore, we believe the grass carp dynamics used in M_g overestimated grass carp consumption of hydrilla within Claytor Lake over the initial 3-year simulation. Conversely, both M_c and M_{sc} predicted plausible reductions of hydrilla biomass densities (0.192 to 0.393 kg m^{-2}) in 2012 based on results from the exclosure study and field observations. However, the grass carp growth and mortality rates used to simulate M_{sc} were derived from a reservoir in which hydrilla biomass remained abundant throughout the study period presumably allowing for rapid growth and greater survival of stocked grass carp (Morrow et al. 1997). In 2011 we found that hydrilla accounted for nearly all of the aquatic plant biomass in Claytor Lake excluding minor localized stands of wild celery, curly pondweed *Potamogeton crispus*, and common waterweed *Elodea canadensis*. Thus, the significant reduction in hydrilla biomass observed in 2012 accompanied with a high grass carp standing stock suggests that growth rates used in M_{sc} and M_g are unlikely to be achieved over the long-term in Claytor Lake.

Grass carp growth rates used in M_c were derived using VBGF parameters estimated from Claytor Lake grass carp between ages 1-4, thus it is possible that this scenario underestimates long-term grass carp growth potential. Grass carp consumption rates are believed to be a function of grass carp size. Therefore an underestimation of size-at-age could lead to inaccurate hydrilla consumption predictions. However, in several piedmont reservoirs in North Carolina where hydrilla was drastically reduced by grass carp within 1-2 years (Manuel et al. 2013), grass carp showed evidence of stunting by reaching just 749 mm TL by age-10 (J.P. Kirk, United States Army Corps of Engineers, unpublished data). Thus, the lower grass carp growth rates estimated for M_c may accurately account for future density-dependent grass carp growth assuming hydrilla remains highly reduced within Claytor Lake. However, continued monitoring of grass carp and hydrilla dynamics within Claytor Lake will be required to fine-tune grass carp growth and survival estimates used in the simulation model.

Evaluation of model assumptions

In the development of our simulation model we made several important assumptions regarding the dynamics of grass carp and hydrilla. Calibration of our hydrilla growth model was dependent upon results from the exclosure experiment. However, the relatively small sample size of exclosures and limited variation in water depth may not have captured the true mean hydrilla density for Claytor Lake as hydrilla density in Claytor Lake was much lower than what has been identified for other waterbodies. Thus, we also ran simulations for each model assuming a mean hydrilla density of 2.5 kg m^{-2} (e.g. Harlan et al. 1985); however, under this scenario grass carp consumption had little impact over the initial 3-year period for all models, and hydrilla continued to expand exponentially. Therefore, we are confident our exclosure experiment adequately represented seasonal hydrilla production in Claytor Lake.

Our hydrilla submodel does not account for annual variability in temperature, precipitation, or water quality parameters which could influence seasonal hydrilla growth. Due to the time constraints of our study, only one year of water temperature monitoring was possible. Since growth of above-ground hydrilla biomass is primarily dictated by ambient temperatures, high variation in temperature among growing seasons could significantly impact actual hydrilla growth rates and biomass density within Claytor Lake. However, grass carp feeding rates are similarly temperature-dependent, which could offset changes in hydrilla production during significantly warmer or cooler growing seasons than observed in 2012. Variation in water quality parameters may also influence hydrilla growth potential, although, water quality data from 2007-2012 along a gradient of sites in Claytor Lake indicates that water temperature, dissolved oxygen, total nitrogen, and total phosphorous have remained relatively constant (D.M. McLeod, Virginia Department of Environmental Quality, unpublished data). Thus, in the absence of grass carp we would expect hydrilla growth and expansion rates to remain relatively constant until carrying capacity is approached. Alternatively, the upper portion of Claytor Lake is prone to turbid conditions after rainfall events. Therefore, extremely wet growing seasons may lead to prolonged turbid conditions that could slow seasonal hydrilla growth and provide grass carp with a competitive advantage. Hence, in this situation grass carp herbivory will likely have a greater impact than reflected by our simulation results.

In developing the grass carp submodel we assumed that grass carp did not emigrate out of the system, and that each stocking cohort exhibited consistent growth and mortality rates annually. During a concurrent telemetry study of grass carp movement patterns in Claytor Lake we observed extremely low emigration rates by stocked grass carp; therefore, this assumption appears justified under current conditions in Claytor Lake. However, the long-term validity of our assumptions regarding consistent grass carp growth and mortality rates is dependent on continued monitoring of the Claytor Lake grass carp population.

Grass carp growth metrics as indicators of hydrilla control

The examination of grass carp growth rates, condition, and production over time may provide managers with a secondary indication of hydrilla control in lieu of extensive vegetation monitoring efforts. For example, similar to our findings Klussman et al. (1987) reported that condition of grass carp in Lake Conroe, Texas, increased significantly one year after stocking, but by the second year post-stocking the condition of grass carp decreased after a majority of the hydrilla biomass was removed from the reservoir. In Devils Lake, Oregon Bonar et al. (1993) combined annual grass carp production with reported feed conversion efficiencies of grass carp (Wiley and Wike 1986) to estimate the amount of plant biomass removed by grass carp over multiple growing seasons. Using grass carp growth metrics to guide hydrilla management efforts requires annual grass carp sampling, which has proven difficult using traditional fisheries sampling methods (Kirk and Morrow 1995; Morrow et al. 1997; Stich et al. 2013). In anticipation of low recapture rates we anchor-tagged a significant proportion of the grass carp stocked in 2012 and 2013 to provide greater precision in long-term growth estimates. Results from our 2012 sampling efforts, and numerous recaptures of tagged fish by VDGIF fisheries biologists during routine electrofishing surveys in fall 2012 and spring 2013 (J.R. Copeland, VDGIF, personal communication) suggest that tagging could be beneficial for future monitoring efforts and growth characterization. While these metrics appear useful as secondary indicators of hydrilla abundance, in situations where maintaining controlled levels of hydrilla without eradication is desired a more nuanced examination of site-specific hydrilla and grass carp dynamics is recommended.

Seasonal grass carp herbivory on hydrilla and native vegetation

Hydrilla control within a system is accomplished when grass carp herbivory exceeds hydrilla growth rates (Noble et al. 1986). The results from our simulation modeling combined with our exclosure experiment found that a grass carp standing stock of approximately 10 metric tons reduced hydrilla biomass by as much as 95% at our exclosure sites, and completely eradicated wild celery within Claytor Lake over the 2012 growing season. Hydrilla consumption by stocked grass carp is often assumed, yet few studies have quantified in-situ reductions in hydrilla density due to grass carp herbivory. Previous efforts to quantify grass carp herbivory on hydrilla biomass have generally used a before-and-after grass carp introduction approach, which usually occurs between alternate growing seasons (Osborne and Sassic 1979; Shireman and Maceina 1981; Webb et al. 1994; Hanlon et al. 2000). By using exclosures we were able to compare ungrazed experimental plots with presumably grazed control plots under identical environmental conditions, whereas between-year comparisons must account for variability in temperature, precipitation, and water quality conditions that could influence plant growth. While not directly comparable to prior methods, in general our results found that despite a more-temperate climate Claytor Lake grass carp were able to rapidly control hydrilla under similar stocking densities as grass carp stocked in Florida (Osborne and Sassic 1979; Shireman and Maceina 1981), Alabama (Webb et al. 1994), and North Carolina reservoirs (Manuel et al. 2013).

Prior to 2012 hydrilla abundance in Claytor Lake had only been quantified spatially; thus, our exclosure experiment also allowed us to estimate peak hydrilla density in the absence of grass carp herbivory. Mean hydrilla density in Claytor Lake at peak growth was lower than that reported for Florida and North Carolina waterbodies (range 2 to 9 kg m^{-2}) possibly due to climactic or trophic state differences (Bowes et al. 1979; Harlan et al. 1985). Consequently, it is possible that lower hydrilla biomass density or annual senescence of hydrilla in Claytor Lake may have contributed to the overall control of hydrilla by grass carp in Claytor Lake by fall 2012. While we were unable to measure hydrilla changes in Claytor Lake over the first growing season post-stocking, a multi-year exclosure experiment could provide even greater insight into expected reductions of hydrilla biomass at various stocking densities and grass carp biomass levels.

Several prior investigations of grass carp grazing patterns have concluded that grass carp generally focus feeding behavior hierarchically, with highly preferred plants such as hydrilla being grazed until elimination before grass carp begin feeding on less-preferred vegetation species (Van Dyke et al. 1984; Leslie et al. 1996). Despite continued presence of hydrilla within adjacent portions Claytor Lake, we observed a complete removal of wild celery, an ostensibly less-preferred plant for grass carp (Van Dyke et al. 1984), due to grass carp herbivory. This finding is especially significant for Claytor Lake and similar waterbodies where submersed plant diversity is low and where maintaining native species is of particular concern. Thus, we recommend that similar methods for excluded grass carp be considered at native vegetation sites even if hydrilla biomass persists within a system.

Future management recommendations

Simulation modeling can be a useful tool for extending our knowledge of dynamic systems and aiding management efforts. In our study, we found that grass carp population dynamics can substantially affect the rate of hydrilla control within a system. Each of the grass carp population submodel scenarios predicted control (or eradication) of hydrilla in Claytor Lake by 2013. Based on our evaluation of these predictions, we recommend that M_c be used to guide future grass carp stocking requirements in Claytor Lake. While our model predicts that stocking intervals can be delayed up to four years, we recommend stocking 1,650 grass carp, or 660 kg of grass carp biomass, every other year in Claytor Lake to ensure grass carp biomass levels remain sufficient for hydrilla control. For example, grass carp survival over the initial two-years post-stocking appears to be low in Claytor Lake (Chapter 2), and long-term survival is currently unknown. Thus, continued low survival at subsequent ages could result in a resurgence of hydrilla and loss of control if grass carp stocking is continually delayed. Alternatively, seasonal environmental conditions may affect hydrilla growth within Claytor Lake. For example, the summer of 2013 was extremely wet resulting in numerous high flow events and prolonged turbid conditions thereby reducing hydrilla growth potential. Therefore, annual grass carp stockings combined with overall poor growing conditions may increase the potential for hydrilla eradication from Claytor Lake. Conversely, an alternate-year stocking program may allow for a minor recovery of hydrilla after poor growth years due to lower grass carp biomass levels, thus increasing the chances of meeting management goals. We also recommend that hydrilla density continue to be monitored on an annual basis in Claytor Lake to validate the efficacy of grass carp stocking efforts. Hydrilla has shown the ability to rapidly rebound after being controlled for several years, presumably due to the extensive persistence of hydrilla propagules and unexpected losses of grass carp biomass from a system (Kirk and Socha 2003, Manuel et al. 2013). Thus, managers should be prepared to revert to annual stocking efforts if hydrilla density levels increase rapidly under the alternate-year stocking strategy. Monitoring grass carp growth and mortality rates within Claytor Lake should also remain a priority to allow for fine-tuning of our simulation model, and to provide important information for developing grass carp management strategies in similar systems. Therefore we recommend that a significant portion of each grass carp stocking group be anchor-tagged, and size and age characteristics be recorded for all grass carp encountered by VDGIF biologists during sampling efforts in Claytor Lake and the New River. While our understanding of grass carp population dynamics remains relatively limited comparative to their use as a biological control in the USA, continued monitoring of the dynamics between grass carp and hydrilla in Claytor Lake and similar systems should allow for greater characterization of these relationships, and ultimately greater precision in management efforts.

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Chapter 4: A survey of the aquatic plant community of the New River upstream of Claytor Lake

Abstract

In 4th-6th order streams such as the New River in Virginia and North Carolina, aquatic plants compose a significant fraction of primary production, and provide complex habitat for myriad fish and macroinvertebrate species. Therefore, changes to the diversity and abundance of aquatic plants could alter the river ecosystem. In our study, we surveyed the aquatic plant community of the New River in response to the documentation of hydrilla *Hydrilla verticillata* within Claytor Lake, a major impoundment of the New River, and recent triploid grass carp *Ctenopharyngodon idella* stocking to manage the hydrilla infestation. The objectives of the survey were to determine whether hydrilla had become established within the reach of the New River upstream of Claytor Lake, and to document the diversity, distribution, and abundance of submersed and emergent aquatic plants currently present within this reach. We determined species composition by recording all plant species encountered during a 39-km float survey from Buck Dam to Allisonia, Virginia, which signifies the start of Claytor Lake. To examine plant abundance we collected 5-min drift-net samples approximately every 4 river-km during the float survey. Overall, we documented 12 aquatic plant species within this reach, whereas hydrilla was not detected. *Elodea canadensis* was the most-abundant species in our drift-net survey, although *Podostemum ceratophyllum* also was observed throughout this reach. Nine of the twelve aquatic plant species have been identified as plants readily consumed by grass carp. Thus it appears that grass carp could alter the aquatic plant community if substantial numbers of grass carp migrate into the New River. Therefore, in combination with continued monitoring for grass carp migrations, we recommend continued monitoring of vegetation abundance, fisheries production,

and water quality within this reach to characterize any future effects of grass carp herbivory on this lotic ecosystem.

Introduction

Aquatic plants are vital to the overall structure and function of lotic ecosystems (Minshall 1978). In mid-sized rivers (4th to 6th order) aquatic plants often comprise a significant fraction of primary production (Minshall 1978; Vannote et al. 1980; Hill and Webster 1983; Rodgers et al. 1983), and are thus especially important in these environments. For example, diverse aquatic plant communities provide complex, heterogeneous habitat for myriad fish and macroinvertebrates species, as well as refuge from predators (Grenouillet et al. 2002; Allen and Castillo 2007). Therefore, changes to the diversity and abundance of aquatic plants has the capacity to severely alter river ecosystems (Holmes et al. 1998), including the goods and services these environments provide to humans (Strange et al. 1999).

Invasive species are one of the foremost threats to the integrity of aquatic ecosystems globally. For example, the monetary cost of invasive species for six developed nations was estimated to be >$US335 billion per year and growing (Pimental et al. 2000). However, the economic effects of invasive species can also be highly local and equally as severe. For example, property values in Wisconsin lakes invaded by Eurasian water milfoil *Myriophyllum spicatum* on average experienced a 13% decline following invasion (Horsch and Lewis 2009). Similarly, hydrilla *Hydrilla verticillata* blocks irrigation canals, hastens sedimentation in reservoirs, interferes with water supplies, impedes boat navigation, and reduces fisheries productivity (Langeland 1996).

Hydrilla was first documented in 2003 in Claytor Lake, Pulaski County, Virginia, which is an impoundment of the upper New River located in the Valley and Ridge physiographic province. In 2011, triploid (sterile) grass carp *Ctenopharyngodon idella* were stocked into the reservoir to manage the expanding hydrilla infestation using an incremental stocking approach; a strategy which aims to gradually reduce hydrilla abundance over several years through periodic low-level grass carp stockings. Long migrations by grass carp have been noted in large rivers in both their native range and the United States (Gorbach and Krykhtin 1988) which could bring them in contact with macrophyte communities in river reaches adjacent to stocked reservoirs. The New River upstream of Claytor Lake is an important aquatic resource for the region including a highly valued sportfishery that could be negatively affected if upstream migration by grass carp leads to reductions in native vegetation. In 2012 we documented low levels of grass carp migration into this reach of the New River through a concurrent telemetry study (Chapter 2), thus it is important to understand the aquatic plant community within this reach to assess the potential for future alterations due to herbivory by migrating grass carp.

No studies have examined the New River aquatic plant community since the late 1970's (Hill and Webster 1983, Rodgers et al. 1983) despite the documentation of hydrilla within the watershed and the recent introduction of grass carp into Claytor Lake. We conducted a drift survey of the aquatic plant communities at eight sites along a 39 km reach of the New River directly upstream of Claytor Lake. The objectives of the survey were to: 1) to determine whether hydrilla had become established within this reach; and 2) document the diversity and abundance of submersed and emergent macrophytes present within this reach to compare with identified plant preferences of grass carp and to assess the potential for future impacts should significant grass carp migrations occur.

Methods

Study Site

The New River originates in the Appalachian highlands of North Carolina and flows northwest through Virginia and West Virginia before joining the Ohio River (Figure 4.1; Hill and Webster 1982). Within southwest Virginia the New River is characterized by a steep gradient, narrow floodplain, and primarily bedrock channel. Our study focused on the 39-km river reach between Buck Dam, the first impoundment upstream of Claytor Lake, and the head of Claytor Lake (generally marked by a set of riffles located near Allisonia, Virginia).

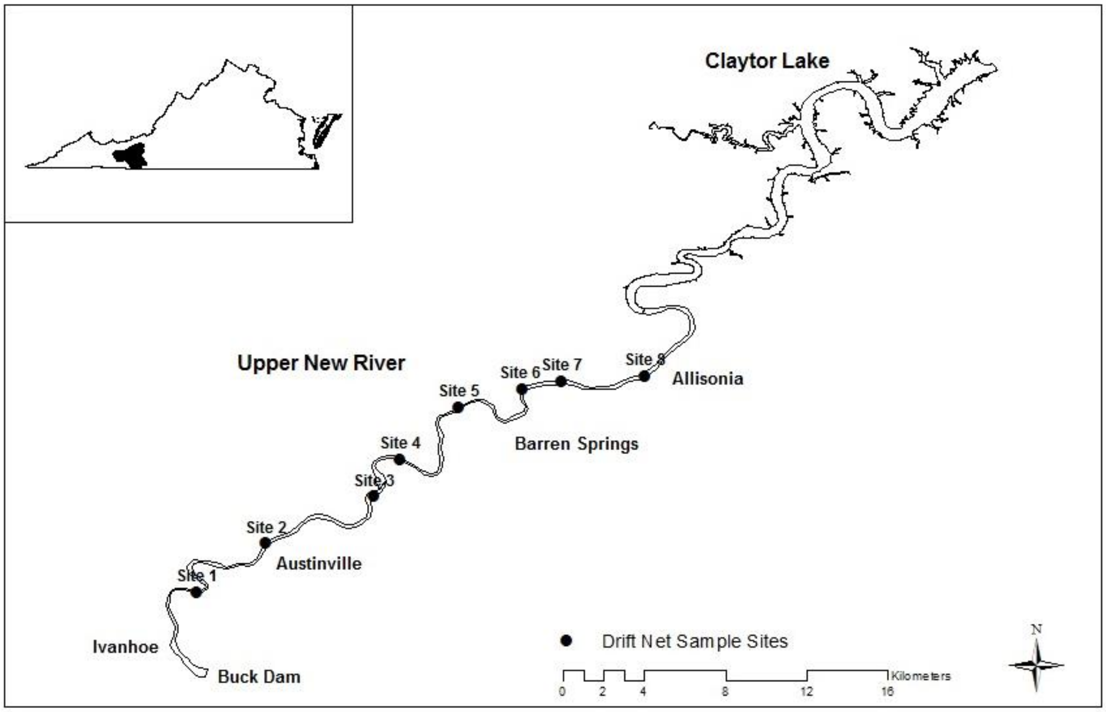

Figure 4.1.—Surveyed section of the Upper New River including locations of drift net sampling sites between Buck Dam near Ivanhoe, Virginia, and the start of Claytor Lake near Allisonia, Virginia.

Assessment of aquatic plant community upstream of Claytor Lake

During July 2012 we surveyed the aquatic plant community by canoe starting at Buck Dam and concluding at the Allisonia rapids at the head of Claytor Lake. We visually surveyed for aquatic plant species along the float, while in deeper pool sections we randomly threw a double-sided rake attached to a rope and slowly retrieved it to check for plant presence. All aquatic plant species were added to a composition list as they were encountered, and representative samples of each plant were placed on ice for verification by taxonomic experts at the Massey Herbarium at Virginia Tech, Blacksburg. To estimate the occurrence and abundance of aquatic plant species at each site, we also collected a single 5-minute drift-net sample using a 7.6-m seine approximately every 5 river-km using methods described by Owens et al. (2001; Table 4.1). All plant material collected during each drift sample was stored on ice, then separated by species, blotted dry, and weighed (g fresh weight, FW) at the conclusion of the survey.

Table 4.1. Site numbers, coordinates (UTM Zone 17N), and approximate locations of aquatic plant drift-net samples collected in 2012 in the New River upstream of Claytor Lake.

Site	UTM (Northing)	UTM (Easting)	Location
1	4077375	505491	Ivanhoe
2	4079776	508234	Austinville
3	4082084	512478	I-77 Overpass
4	4083925	513523	Fosters Falls
5	4086499	515813	Route 626
6	4087376	518319	Barren Springs
7	4087783	519863	Ledge Rock Rd
8	4088027	523163	Allisonia

Results

Whereas Hill and Webster (1984) identified 6 aquatic plant species present within this reach of the New River, we identified 12 species and the macro-alga *Chara* Linnaeus, of which 9 have been identified as readily or moderately consumed by grass carp (Table 4.2; Opuszynski and Shireman 1994). We did not detect hydrilla within this river stretch. The highest amount of plant biomass collected in our drift-net samples was at site 5 (365 g; Figure 4.2). Both *Elodea canadensis* and *Potamogeton crispus* were collected at all drift-sample sites (Table 4.3). While absent from the site-6 drift sample, *Podostemum ceratophyllum* also was observed throughout the entirety of the survey primarily within shallow runs and riffles. Overall, *E. canadensis* comprised more than 62% of the total plant biomass sampled during the drift-net survey. *P. ceratophyllum* also was prevalent in the drift net survey, consisting of approximately 23% of total plant biomass collected.

Table 4.2. List of aquatic plant species documented during a float survey of the New River between Buck Dam and Allisonia, Virginia during July 2012. Determinations of prior species documentations were based on survey results from Hill and Webster (1984).

Common name	Scientific name	Classification	Prior documentation
Water Weed*	*Elodea canadensis*	submersed	yes
Curly Leaf Pondweed*	*Potamogeton crispus*	submersed	yes
Longleaf Pondweed*	*Potamogeton nodosus*	floating-leaved	no
Leafy Pondweed*	*Potamogeton foliosus*	submersed	no
Wild Celery*	*Vallisneria americana*	submersed	yes
Riverweed	*Podostemum ceratophyllum*	submersed	yes
Muskgrass*	*Chara* Linnaeus	algae	no
Water Willow	*Justicia americana*	emergent	yes
Giant Duckweed*	*Spirodela polyrhiza*	floating-leaved	no
Arrowhead*	*Sagittaria* sp.	emergent	no
Common Cattail*	*Typha latifolia* L.	emergent	yes
American Bulrush	*Schoenoplectus pungens*	emergent	no
Grassleaf Mudplantain	*Heteranthera dubia*	submersed	no

*-Indicates plants identified as readily, or moderately consumed by grass carp (Opuszynski and Shireman 1994)

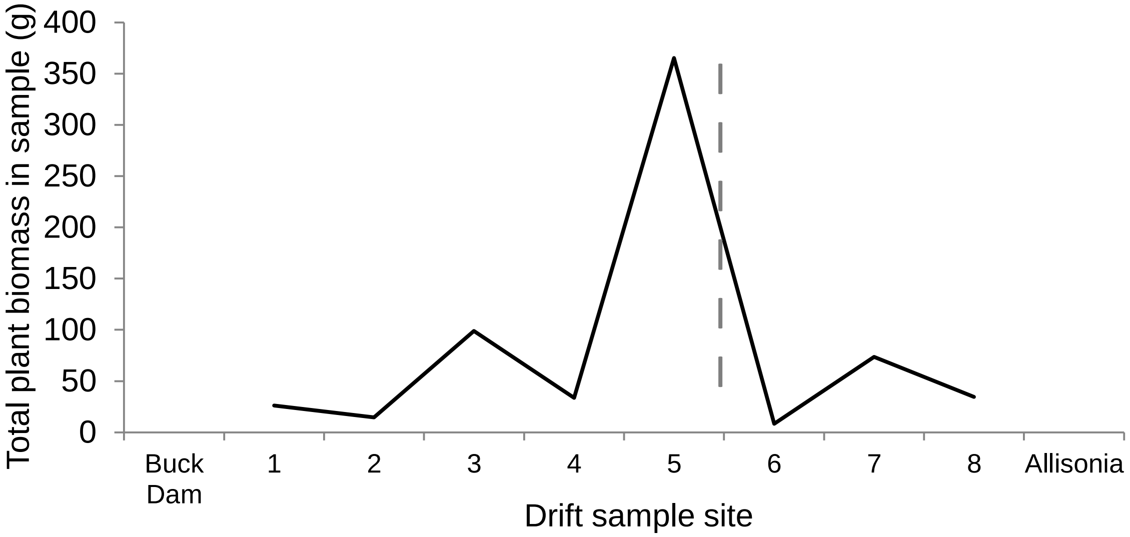

Figure 4.2. Total plant biomass (g) collected in drift-net samples taken in July 2012 at eight sites in the New River between Buck Dam and Allisonia. The dashed line indicates the furthest point upstream of Claytor Lake we documented grass carp during a concurrent telemetry study (Chapter 2).

Table 4.3. Species composition and percent of the total sample biomass for each species from drift-net samples taken approximately every 5 river-km during the July 2012 aquatic plant survey of the New River between Buck Dam and Allisonia, Virginia.

		Percent of total drift-net sample biomass by site							
Common Name	Scientific Name	1	2	3	4	5	6	7	8
Water weed	*Elodea canadensis*	29.01	46.94	9.61	9.50	87.52	58.33	69.25	20.17
Curly leaf pondweed	*Potamogeton crispus*	0.38	5.44	1.11	0.30	10.84	29.76	12.93	42.07
Longleaf pondweed	*Potamogeton nodosus*	4.58	6.12	1.52	-	0.68	-	-	-
Leafy pondweed	*Potamogeton foliosus*	-	-	0.10	0.30	0.41	1.19	12.93	20.46
Wild celery	*Vallisneria americana*	0.38	12.24	0.20	0.59	0.30	10.71	-	-
Riverweed	*Podostemum ceratophyllum*	65.65	29.25	87.46	89.32	0.25	-	4.76	17.29
Muskgrass	*Chara* Linnaeus	-	-	-	-	-	-	0.14	-

Discussion

Aquatic plant community of the New River upstream of Claytor Lake

Understanding aquatic plant communities in mid-sized rivers can provide important insight into ecosystem structure and overall stability (Minshall 1978; Gregg and Rose 1982). However, comparatively few studies have addressed riverine aquatic plant communities in the United States (Franklin et al. 2008). Our study identified a more-diverse aquatic plant community in this stretch of the New River than prior investigations (Hill and Webster 1984). In both terrestrial and aquatic plant communities, greater diversity and abundance of native species is believed to provide resiliency against the establishment of introduced species (Dukes 2001; Capers et al. 2007; Larson et al. 2013) which could explain the apparent absence of hydrilla within this reach. Suitable habitat for aquatic plants in riverine environments is often limited by flow conditions and substrate type leading to patchy distributions (Butcher 1933; Sand-Jensen and Madsen 1992; Sprenkle et al. 2004). Similarly, the plant biomass collected in our drift-net samples varied greatly among sites which could be attributed to the high gradient and primarily bedrock channel of the upper New River. The lushest stands of more-abundant species such as *V. americana*, *P. foliosus*, and *E. canadensis* appeared to be highly localized at depositional zones. Therefore these depositional areas may be of significant ecological importance for aquatic biota within this reach. Prior to our study Hill and Webster (1984) identified *Podostemum ceratophyllum* as the most-abundant plant species within this reach of the New River while *E. canadensis* accounted for just 0.03% of macrophyte coverage. Conversely, the results from our drift-net survey indicate *E. canadensis* may be the most-abundant macrophyte possibly suggesting a shift in community structure. *P. ceratophyllum* was also abundant in our drift-net surveys; although, due to its epilithic nature our sampling methods may underestimate its true abundance in this reach of the New River. Additionally, Hill and Webster (1984) used aerial photography combined with ground-truthing to determine overall coverage and abundance of plant species which could further explain the observed differences in results. No emergent species were collected within our drift-net survey; however, we observed patchily distributed stands of *Justicia americana* throughout the survey. Hill (1981) identified *J. americana* as the most productive macrophyte within the upper New River, although he speculated its localized distribution limited the plants overall contribution to the energy budget. While our study provides a much needed understanding of the current aquatic plant community of the New River upstream of Claytor Lake, future monitoring may also be important for identifying potential alterations of plant abundance or community structure due to grass carp herbivory.

Evidence and implications of grass carp herbivory on P. ceratophyllum

Within swift-flowing Appalachian rivers *P. ceratophyllum* can be the dominant source of autotrophic production (Hill and Webster 1983), may elevate macroinvertebrate production (Hutchens et al. 2004), and is associated with higher stream-fish abundance (Argentina et al. 2010), therefore grass carp herbivory on *P. ceratophyllum* could have ecosystem-scale repercussions. Currently, no studies have identified *P. ceratophyllum* as preferred forage for grass carp; however, we incidentally observed *P. ceratophyllum* within the alimentary tract of numerous grass carp collected near the Allisonia rapids through a concurrent growth study in fall 2012 (Chapter 3). The presence of hydrilla in nearby shoal areas of Claytor Lake at the time of our grass carp sampling efforts offers greater circumstantial evidence of grass carp preference for *P. ceratophyllum. P. ceratophyllum* has been noted as a preferred macrophyte for herbivores such as Canadian geese *Branta canadensis* and crayfish *Procambarus spiculifer* (Parker et al. 2007); however, the voracious feeding pattern of grass carp on highly preferred plant species (up to 100% of body weight per day; Osborne and Riddle 1999) is of particular concern. For example, prior to 2012 *P. ceratophyllum* was abundant on the substrate at the Allisonia rapids, whereas in fall 2012 the substrate in this area was apparently devoid of *P. ceratophyllum* presumably due to grass carp herbivory (J.R. Copeland, Virginia Department of Game and Inland Fisheries [VDGIF], personal communication). Prior studies have noted overall declines of *P. ceratophyllum* populations within Appalachian streams (Munch 1993; Argentina et al. 2010) which, if transferrable to the New River, could be compounded by grass carp herbivory in this reach.

Implications of potential grass carp migration

The majority of macrophyte species observed in our examination have been documented as preferred forage for grass carp that could migrate into that area. These findings combined with the localization of the most-abundant plant species identified during our survey indicate that the plant community could be vulnerable to alterations due to grass carp herbivory. Currently, the overall migration rates of Claytor Lake grass carp beyond our observations during 2012 are unknown; however, additional evidence indicates migration rates could increase as hydrilla abundance declines in Claytor Lake, and as grass carp approach maturity. Our telemetry study of juvenile grass carp stocked into Claytor Lake found that just 2 of 75 radio-tagged fish migrated into the New River over the 2-yr study (Chapter 2), although the instances of migration occurred in 2012 after hydrilla abundance in Claytor Lake was significantly reduced (Chapter 3). Thus migration rates could increase as a result of grass carp searching for food if vegetation resources remain limited within Claytor Lake. Additionally, life stage of grass carp is believed to influence movement patterns (Gorbach and Krykhtin 1988). For example, mature grass carp (600-730 mm total length [TL], 4.0-6.0 kg) stocked in Lake Guntersville, Alabama showed significantly higher rates of movement than juveniles, and completed migrations as far as 71 km upstream (Bain et al. 1990). Accordingly, 32 grass carp (mean TL 716 mm) were sampled within the New River upstream of Claytor Lake in the spring and early summer 2013 during electrofishing assessments, whereas only 4 grass carp had been sampled in this reach in the previous two years since grass carp were stocked in Claytor Lake (J.R. Copeland, VDGIF, unpublished data). Alternatively, the New River was subject to high flows throughout the spring and early summer of 2013 and 27 of the grass carp collected in 2013 were captured within close proximity of Allisonia, thus the increase in grass carp collections may be a result of high flows creating more-accessible habitat.

Research implications

Based on our examination of the aquatic plant community in the New River upstream of Claytor Lake we contend that annual surveys of vegetation abundance, fisheries production, and water quality combined with continued monitoring of grass carp migration could provide an important case study on the effects of grass carp in lotic ecosystems. Grass carp have been documented in numerous large rivers throughout the United States (Guillory and Gasaway 1978; Pflieger 1978; Elder and Murphy 1997) yet examinations of the effects grass carp have on the form and function of aquatic ecosystems has been limited to lakes and reservoirs. In Lake Conroe, Texas the complete removal of macrophytes by grass carp resulted in a major biomass shift to more-pelagic fish species (Bettoli et al. 1993), increased nutrient levels, and decreases in water clarity due to higher algal biomass (Maceina et al. 1992). However, river systems differ greatly in structure and function compared to lentic environments thus limiting comparability in the assessment of potential grass carp effects. Hydrilla continues to present major threats to aquatic ecosystems at all scales including to the integrity of riverine aquatic macrophyte communities. Grass carp will likely remain a major management tool for addressing invasive hydrilla infestations. Future work on the impacts of grass carp on the macrophyte communities of the New River will provide an important case study of the feasibility of grass carp as a management tool for hydrilla balanced against the conservation needs of upriver macrophyte communities.

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Chapter 5: Conclusions

Summary

Grass carp movement patterns, and habitat use in an Appalachian reservoir

From 2011 to 2013 we used radio-telemetry methods to examine the movement patterns, habitat use of two stocking cohorts of triploid grass carp in Claytor Lake, a riverine Appalachian reservoir, in response to concerns about their efficacy as a biological control in such a system. Our results combined with concurrent changes in hydrilla coverage suggest that grass carp can be effectively used to manage hydrilla in a riverine reservoir such as Claytor Lake. Only 3% of radio-tagged grass carp emigrated from Claytor Lake in to the New River, and after a 1-month acclimation period movements of grass carp were highly localized primarily within areas known to be colonized by hydrilla. Accordingly, Claytor Lake grass carp selected for shoal, cove, and tributary habitats, each of which supported hydrilla during the study period, while they generally avoided additional non-vegetated habitats. Temperature-related variables were positively correlated with observed grass carp movements and explained the greatest proportion of variation for both stocking cohorts. Conversely, flow-related variables did not explain a significant proportion of the variations in grass carp movement observed during our study possibly indicating that the potential for long-range movement by grass carp is not enhanced in a riverine environment. However, the current literature combined with more-recent grass carp collections in the New River in spring 2013 indicate that migration potential may increase as grass carp age. Hence, an examination of mature grass carp movement patterns and habitat use in both reservoir and lotic ecosystems could benefit future management strategies, or grass carp removal efforts in cases where non-target vegetation is impacted.

Survival rates of grass carp in an Appalachian reservoir

Grass carp survival in Claytor Lake was considerably lower than reports from other large reservoirs in the USA, suggesting that annual survival rates of grass carp are variable among systems. We speculate that size-at-stocking combined with a diverse group of piscivorous predators, and also significant reductions in vegetation abundance within Claytor Lake may explain the lower survival rates observed for grass carp. By using radio-telemetry to estimate initial survival of grass carp stocked into a new system we identified lower survival rates than expected, thus allowing managers to actively adapt future stocking strategies to maintain desired grass carp densities. However, a greater understanding of grass carp vulnerability to avian and mammalian predators could provide important insight into ideal stocking sizes which minimizes grass carp predation, or conversely provide managers with an expected mortality rate due to predation that could be incorporated into stocking programs.

Grass carp growth metrics as indicators of hydrilla control

We monitored annual growth, production, and condition of stocked grass carp in Claytor Lake between 2011 and 2013 to relate with observed changes in hydrilla abundance. Over the 2011 growing season in Claytor Lake grass carp grew rapidly (increase of 224 mm TL, 2.9 kg), estimated production was 6.07 kg ha^{-1}, and condition factor increased dramatically for all length-groups of sampled grass carp. Conversely, growth of grass carp over the 2012 growing season slowed substantially, and estimated production (1.93 kg ha^{-1}) and condition factor declined after hydrilla abundance was greatly reduced. These results suggest grass carp growth and associated metrics are primarily dictated vegetation abundance within a system, and can be used as a secondary indication of hydrilla control in lieu of extensive vegetation monitoring efforts.

Alternatively, the long-term monitoring of grass carp growth in conjunction with vegetation monitoring could provide managers the ability to identify trends important for improving grass carp stocking strategies.

Seasonal grass carp herbivory on hydrilla and native vegetation in an Appalachian reservoir

We conducted an exclosure study over the 2012 growing season to characterize grass carp herbivory rates on both native vegetation and hydrilla in Claytor Lake. All native vegetation not located within our exclosures was eradicated early in the growing season. Similarly, hydrilla density at the control sites averaged 0.06 kg m^{-2}, whereas hydrilla density within the exclosures averaged 1.25 kg m^{-2}. These results, combined with our estimates of grass carp production and survival, indicate that a grass carp standing stock of approximately 10 metric tons reduced hydrilla density by 95% over the 2012 growing season. Peak hydrilla density (determined by exclosure results) in Claytor Lake was lower than reports for waterbodies in lower latitudes, thus it is possible that in more-temperate climates with shorter growing seasons lower stocking densities of grass carp may be adequate for achieving intermediate levels of hydrilla control. Additionally, grass carp targeted ostensibly less-preferred native vegetation species while hydrilla was still present within Claytor Lake, albeit at low densities. Therefore, similar methods of excluding grass carp are likely necessary to conserve native vegetation in systems with moderate hydrilla infestations such as Claytor Lake.

Development of a dynamic stocking model to guide long-term hydrilla management efforts

We developed a dynamic stocking model utilizing hydrilla growth dynamics observed in Claytor Lake, and grass carp population dynamics to aid managers in identifying stocking rates required to maintain low levels of hydrilla coverage. The greatest uncertainty in the development of our model was long-term growth and mortality rates of grass carp as these factors have rarely been addressed. Therefore, we developed 3 grass carp submodels to evaluate how variations in grass carp growth and survival could affect long-term stocking requirements in Claytor Lake. The grass carp submodels included initial growth and mortality rates for Claytor Lake (low growth potential/high mortality), and those reported for Lake Gaston, Virginia/North Carolina (linear growth/average mortality), and Santee-Cooper Reservoir, South Carolina (high growth/low mortality). The model utilizing grass carp population dynamics from Claytor Lake predicted hydrilla could be maintained at target levels by a standing stock of 5 to 6 metric tons of grass carp biomass, whereas the remaining scenarios predicted hydrilla eradication early in the management process. These results indicate grass carp population dynamics within a system can have a significant influence on long-term hydrilla management efforts. Therefore, greater characterization of these factors in should enable greater precision in hydrilla management efforts.

Assessment of the aquatic plant community upstream of Claytor Lake

In 2012 we conducted a float survey of the New River upstream of Claytor Lake to determine if hydrilla had become established within this reach, and to describe the aquatic plant community to compare with identified plant preferences of grass carp. We did not detect hydrilla during our survey. Overall, we identified 12 aquatic plant species within this stretch, including 9 plant species previously documented as preferred plants for grass carp. Additionally, we identified grass carp consumption of *Podostemum ceratophyllum* in areas where hydrilla was present indicating *P. ceratophyllum* is also a preferred plant for grass carp. Thus, if high rates of grass carp migration occur it is likely the plant community will be altered. Currently no studies have examined the effects of grass carp herbivory on lotic ecosystems. While grass carp migration rates currently appear low, there is the potential for increased migration due to stocked grass carp approaching maturity, and reduced hydrilla abundance in Claytor Lake. Therefore, continued monitoring for potential changes in the form and function of the New River as a result of grass carp herbivory could provide an important case study for managers considering the use of grass carp as a management tool in open systems.