DRAFT

Grass Carp: Lakes and Large Impoundments

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May 1993

Grass carp *Ctenopharyngodon idella* (Val.), a globally important food fish, was first introduced into the United States in 1963 by Auburn University and the U. S. Fish and Wildlife Service to investigate the prowess of this Asian species at consuming aquatic vegetation (Shelton et al. 1981; Allen and Wattendorf 1987). These large minnows (Cyprinidae) are very attractive for vegetation management because they readily eat plants, are hardy, and are eurythermic. Stevenson (1965) reported that 38 grass carp in a 0.04 ha pond endured five weeks under solid ice, then summer temperatures of 35.6°C. Opuszynski (1967) found that grass carp are very tolerant of low dissolved-oxygen conditions; lethal concentrations were between 0.3 mg/L and 0.4 mg/L. Also called the white amur, these fish can grow to 50 kg (Shireman and Smith 1983). Recently, a 44 kg (97 lb) specimen was captured near Deltona, Florida. In this chapter we will review available information on grass carp biology and use of these fish to manage aquatic plants in lakes and larger impoundments, with particular attention to approaches that minimize long-term undesirable effects on natural systems. We emphasize that grass carp have proven to be voracious herbivores throughout the world, and once they are stocked, the removal techniques for larger aquatic systems are inefficient (Shireman and Smith 1983; Leslie et al. 1987). Careful planning is definitely required before integrating grass carp into routine aquatic plant management programs. Towards that end, it seems prudent to begin with a brief review of the development of triploid grass carp.

Grass carp are endemic to the large river systems of Asia (from the Amur River south) and require flowing water to spawn naturally (Stanley et al. 1978; Leslie et al. 1982). Grass carp do not naturally spawn in static waterbodies; thus, fears that they will reproduce and overpopulate a lake are unfounded. However, escaped grass carp have apparently established reproductive populations in the Mississippi and Missouri River systems (Conner et al. 1980; Brown and Coon 1991). Brown and Coon (1991) expect these populations to expand in distribution. Of primary concern is the impact that large reproductive populations could have on the native biota and on wetland food webs where aquatic vegetation is especially important (Allen and Wattendorf 1987). But it seems that, unlike the silver carp (*Hypophtalmichthys molitrix*), grass carp have not generally built up large destructive populations on their own in the wild (Stanley et al. 1978).

None the less, since the early 1970's, a fear of mass reproduction of grass carp has stimulated research efforts to produce monosex or sterile fish. Stanley (1976) developed techniques for hatchery production of monosex grass carp. Lake Conway, Florida, was stocked with the all-female progeny resulting from this work. Problems encountered were that the fish were not sterile; some males were produced; and production of actual gynogenetic fish was very low, greatly increasing cost. Attempts at surgical sterilization by gonadectomy have proven futile because grass carp regenerate viable sex organs (Clippinger and Osborne 1984; Underwood et al. 1986).

In 1978, Hungarian workers reported developing a theoretically sterile triploid hybrid from crossing male bighead carp (*Hypophthalmichthys nobilis*) and female grass carp (Marian and Kraznai 1978). They were trying to increase growth rates through heterosis (the hybrid-vigor phenomenon) to enhance production of food for human consumption. The hybrid contained two chromosome complements from grass carp and one from bighead carp and was found to be very similar in morphology and behavior to grass carp (Beck et al. 1980; Sutton et al. 1981). However, progeny from such crosses under operational conditions proved to be heterogeneous (few actual triploid hybrids were produced); mortality was high; and feeding rates were much lower than those of diploid grass carp (Cassani et al. 1982; Osborne 1982; Shireman et al. 1983; Wattendorf and Shafland 1983; Wiley and Wike 1986). Given these results, Osborne (1982) doubted that the triploid hybrid could be effectively used in aquatic plant management operations.

In 1984, an Arkansas fish farmer reported successful production of a true triploid grass carp in commercial numbers (Malone 1984). The fish were hardy, and their growth and behavior were similar to that of diploid grass carp (Wattendorf and Anderson 1984; Sutton 1985; Cassani and Caton 1986a; Wiley and Wike 1986; Allen and Wattendorf 1987). These similarities were important--it meant that previous research work on diploid grass carp could be generally valid for triploid grass carp.

The triploid condition is induced by heat-shock or hydrostatic pressure-shock (Cassani and Caton 1986b; Thompson et al. 1987) of fertilized grass carp eggs, which results in retention of three chromosome complements. Triploid cyprinids are theoretically sterile, and recent information suggests that triploid grass carp are functionally sterile (Purdom 1983; Thorgaard 1983; Allen and Wattendorf 1987). Triploid grass carp spermatids are morphologically abnormal, probably due to variable DNA content from random assorting of the extra chromosome complements (Allen et al. 1986). Of every billion spermatids, only 60 will contain a true haploid (Allen et al. 1986). Set loose in a river with diploid grass carp, the triploid form would offer little additional reproductive potential. In fact, triploids may help disrupt diploid reproduction, as sterile fruit flies are used to disrupt wild fruit fly reproduction (Allen et al. 1986).

On December 2, 1984, the U. S. Fish and Wildlife Service issued a biological opinion that female triploid grass carp are functionally sterile and that triploid sperm are probably nonfunctional (Sanders et al. 1991). The formal statement opens the door to wider use of triploid grass carp in the U. S. Only Coulter counter-verified triploid grass carp are permitted to be stocked into Florida waters for aquatic plant management (Wattendorf 1986; Allen and Wattendorf 1987). We agree with Thompson et al.

(1987) that because of techniques allowing mass production of triploid grass carp, use of diploid grass carp in plant control operations should be discontinued, particularly in natural areas and near large river systems.

GROWTH AND FEEDING

Understanding the biological and ecological dependencies of grass carp feeding dynamics is essential for adjusting stocking strategies to local climatic circumstances. Grass carp are herbivorous at lengths greater than 3.0 cm and they show definite food preferences. Their feeding rates are strongly dependent on age and size of fish, ambient temperatures, dissolved oxygen, and size, location, and species of plants present (Stroganov 1963; Hickling 1966, 1967; Fischer 1968; Krupauer 1971; Prowse 1971; Opuszynski 1972; Sutton 1977; Osborne and Sassic 1981; Van Dyke et al. 1984; Sutton and Vandiver 1986; Wiley and Wike 1986; Leslie et al. 1987). Grass carp will not actively seek out animal prey, but they will consume them when presented in the absence of plant matter; grass carp will lose weight in ponds devoid of vegetation (Prowse 1966; 1971; Rottman and Anderson 1976).

The growth rate of grass carp can be extraordinary under favorable conditions (up to 29 g/day)--and practically zero under crowded conditions or where preferred food is absent (Shelton et al. 1981; Sutton and Vandiver 1986). Grass carp have a very short gut (for a herbivore), which allows them to process and eliminate plant material quickly. As cyprinids, grass carp have no jaw teeth, but they have highly specialized pharyngeal teeth and a horny pad in the roof of the pharynx, which together act as effective grinders allowing digestion of 60 to 70 percent of the nutrients in the vegetation consumed (Stroganov 1963; Hickling 1966; Cross 1969; Van Dyke and Sutton 1977). Despite incomplete digestion (Hickling 1966), food conversion ratios of dry weight duckweed to grass carp flesh are surprisingly good (large fish 2.7; small fish 1.6, see Shireman et al. 1978a). Van Dyke and Sutton (1977) reported similar feed conversion rates. However, Wiley and Wike (1986) reported that assimilation of food averaged only 27 percent, and thus considered triploid and diploid grass carp to be inefficient, implying reliance on a low-efficiency/high-volume feeding strategy. In contrast, Van Dyke and Sutton (1977) and Shireman et al. (1978a) considered these fish surprisingly efficient. Whatever the semantics, there is no doubt that grass carp process a lot of plant material quickly, and such quantities of egested plant matter from a large number of fish can be of limnological significance (Hickling 1966).

It is important to understand that the reported differences in temperature at which grass carp begin to feed may be due in part to regional acclimation. Grass carp from temperate regions may begin to feed intensively at lower temperatures--an important consideration when using models to predict stocking rates. Also, dissolved-oxygen concentrations below 4 mg/L can reduce plant consumption rates by 40% (Rottman 1977). European and Russian workers found that grass carp feed intermittently at 3-9 ^{o}C, feed steadily at 10-16 ^{o}C, and begin to feed intensively at temperatures above 16 ^{o}C, with optimal feeding at 21-26 ^{o}C (Stroganov 1963). Opuszynski (1972) reported that, in Poland, intensive feeding began at 20 ^{o}C (50% body weight/day); at 22 ^{o}C grass carp were eating at 120-122% body weight/day. Edwards (1974) in New Zealand found that between 20 ^{o}C and 23 ^{o}C grass carp consumed as much as their body weight per day. In the United States, feeding begins at about 11 ^{o}C (Wiley and Wike 1986), is optimal between 20 ^{o}C and 30 ^{o}C, and declines above 30 ^{o}C (Sanders et al. 1991). Shireman et al. (1983) found that

Table 1. Grass carp and triploid grass carp feeding preference lists based on experimental data from the United States and New Zealand.

Edwards (1974) Percent consumption of selected aquatic plants over five days by grass carp in New Zealand.

plant species	14 g fish	375 g fish
Nitella	100	100
duckweeds	100	100
Elodea canadensis	100	100
Callitriche stagnalis	50	100
Paspalum sp.	50	100
Nasturtium sp.	45	100
Potamogeton crispus	34	100
Azolla rubra	0	34
Myriophyllum propinquum	0	24
Largarosiphon major	0	20
Ceratophyllum demersum	--	20
Egeria densa	--	0
Mimulus guttatus	0	--

Bowers et al. (1987) Overall preference ranking for 12 species of aquatic plants in the Pacific northwest US. Triploid grass carp.

HIGHLY PREFERRED
- *Potamogeton crispus and P. pectinatus*
- *P. zosteriformes*
- *Elodea canadensis*
- *Vallisneria americana*

VARIABLY PREFERRED
- *Myriophyllum spicatum*
- *Ceratophyllum demersum*
- *Utricularia vulgaris*
- *Polygonum amphibium*

NON-PREFERRED
- *Potamogeton natans*
- *Brasenia schreberi*
- *Egeria densa*

Sutton and Vandiver (1986) approximate order of preference for selected aquatic plants in Florida.

- *Hydrilla verticillata*
- *Chara spp.*
- *Najas guadalupensis*
- *Egeria densa*
- *Wolffia*
- duckweeds
- *Azolla* spp.
- *Potamogeton* spp.
- *Ceratophyllum demersum*
- *Panicum repens*
- *Typha* spp.
- *Stratiotes aloides*
- *Nasturtium* spp.
- *Myriophyllum spicatum*
- *Vallisneria americana*
- *Myriophyllum aquaticum*
- *Eichhornia crassipes*
- *Pistia stratiotes*
- *Nymphaea* spp.
- *Nuphar luteum*

Chapman and Coffey (1971) Feeding preference of grass carp in New Zealand, North island fish size 3-10 kg.

- *Nitella Chara*
  - *Callitriche stagnalis*
  - young *Largarosiphon major* (Lake Rotoiti)
  - *Potamogeton crispus*
  - *P. ochreatus*
  - young *Largarosiphon major* (Lake Karapiro)
  - *Lemna/Spirodela*
  - *Egeria densa* (Waikato River)
  - *Elodea canadensis* (Lake Rotoiti)
  - *Potamogeton cheesemanii*
  - old *Largarosiphon major*
  - *Vallisneria gigantea*
  - *Ceratophyllum demersum*
  - *Salvinia herzogii*
- *Limnosella lineata/Triglochin striata/ Lilaeopsis lacustris/Isoetes kirkii*
  - *Elodea canadensis* (Western Springs)
  - *Myriophyllum propinquum*
  - *Myriophyllum elatinoides*
- *Egeria densa* (Western Springs)
  - Rejected: Tough *Largarosiphon* stems; *Vallisneria* rootstocks; *Typha angustifolia; Myriophyllum brasiliense*.

Van Dyke et al. (1984) apparent food preferences of grass carp in Florida lakes over a 10-year period.

PREFERRED
- *Hydrilla verticillata*
- duckweeds
- filamentous algae

Brasenia schreberi
- *Ceratophyllum demersum*
- *Myriophyllum laxum*
- *Potamogeton illinoensis*
- *Utricularia* spp.

INTERMEDIATE
- *Salvinia minima*
- *Typha* spp.
- *Sagittaria lancifolia*
- *Eichhornia crassipes*
- *Panicum hemitomon*
- *Pontederia cordata*
- *Eleocharis* spp.
- *Panicum repens*

NON-PREFERRED
- *Myriophyllum spicatum*
- *Alternanthera philoxeroides*
- *Vallisneria americana*
- *Nymphaea odorata*
- *Ludwigia octovalis*
- *Hydrocotyl* spp.
- *Cladium jamaicense*

grass carp ceased feeding below 16 ^{o}C in Florida, but began to feed on a rising temperature even when below 16 ^{o}C. Kilambi and Robison (1979) found no significant differences in feeding rates between 18.3 ^{o}C and 29.4 ^{o}C; they noted a two-fold increase in consumption between 12.8 °C and 29.4 °C.

Density is also an important factor. Growth is inversely proportional to fish density even if supplemental feeding is supplied (Shelton et al. 1981). Kilambi and Robison (1979) found that food consumption was 2.4 fold higher at a density of 5 fish in 1,135-L tanks than at 5 fish in 227-L tanks at the same temperature. Most growth/plant-consumption estimates used in models may be underestimates because of high densities used in pond/laboratory studies.

Larger grass carp seem to consume less in relative terms but do generally consume larger absolute quantities of plant matter (Clugston and Shireman 1987). Smaller grass carp may consume more than 100 percent of their body weight per day (Opuszynski 1972; Venkatesh and Shetty 1978). Sanders et al. (1991) reported that fish weighing less than 3 kg feed at a rate of about 100% body weight per day; fish weighing 3-6 kg feed at about 75% body weight per day. Grass carp larger than 6 kg in weight consume 26-28% of their body weight per day (Shireman and Maceina 1981). However, Osborne and Sassic (1981) reported that while 2.5 kg grass carp ate Brazilian elodea (*Egeria densa*) at an average rate of 76% body weight per day over 28 days, and 6.5 kg fish averaged 25%, the 14.1 kg fish averaged only 0.5% in Florida experimental ponds. They conclude that very large, older fish may not be as effective for plant control purposes. In central Florida, grass carp can reach 14 kg in their third year (Osborne and Sassic 1981). However, grass carp (50 fish/ha) are known to have effected near total elimination of aquatic plants in three central Florida lakes for more than 15 years (Leslie et al. 1987). Thus, both the age of fish and climatic conditions (i.e., days per year water temperatures exceed 18.3 °C) must be considered when grass carp are to be used in plant control operations.

FOOD SELECTIVITY

Food selectivity of grass carp is a critical variable to consider in any aquatic plant management plan. Representative preference lists for diploid and triploid grass carp in divergent climatological regimes are presented in Table 1. In general, small grass carp select small or soft plants like duckweeds, filamentous algae or softer pondweeds. As the fish grow in size, filamentous algae become less preferred; duckweeds and pondweeds are still preferred, but fibrous plants are accepted more readily (Opuszynski 1972; Rottman 1977). Food preferences can be influenced by the age, size, physiological state of the grass carp, feeding history, and also by environmental conditions (Stroganov 1963; Rottman 1977; Colle et al. 1978). Small and large grass carp tend to be less selective at higher temperatures--the order of preference changes little but some of the less preferred species may be grazed more frequently (Stroganov 1963; Edwards 1974). Bowers et al. (1987) found no differences in preferences between diploid and triploid grass carp, and no effects on preference related to fish density. Triploid grass carp preferences did not change between experiments conducted at 15 °C, 20 °C, and 25 °C (Bowers et al. 1987).

Perhaps the most important consequence of food preference to be considered by resource managers is that grass carp feed little on non-preferred aquatic plants until all (or nearly all) of the more preferred species are eliminated. They will, however, simultaneously graze several species of plants that are at about the same preference level (Edwards 1974; Fowler and Robson 1978). Selective grazing by grass carp may actually result in expansion of aggressive unpalatable species (such as Eurasian watermilfoil) until

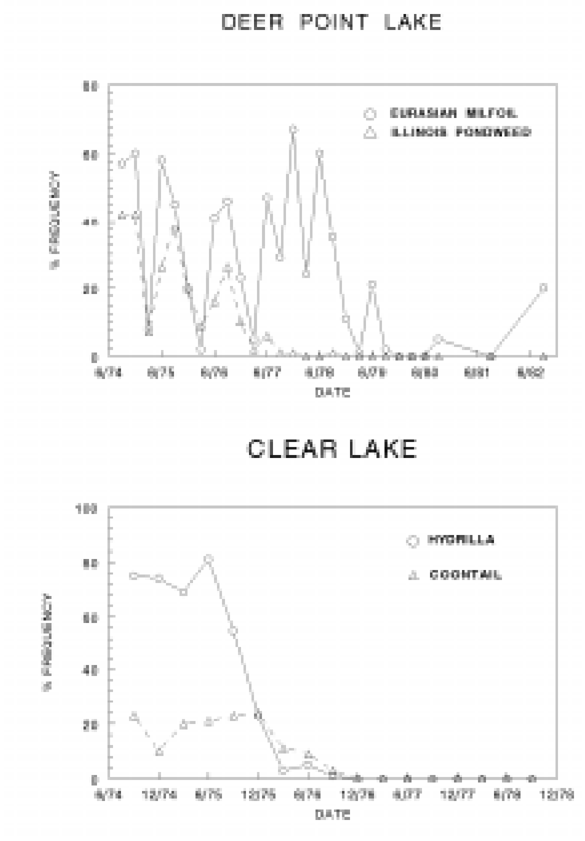

Figure 1. Frequency of occurrence of Eurasian watermilfoil and Illinois pondweed in Deer Point Lake (stocked with 62 diploid grass carp/ha in 1976), Florida, and hydrilla and common coontail on transects in Clear Lake (stocked with 50 diploid grass carp/ha September 1974), Florida. Modified from Van Dyke et al. (1984).

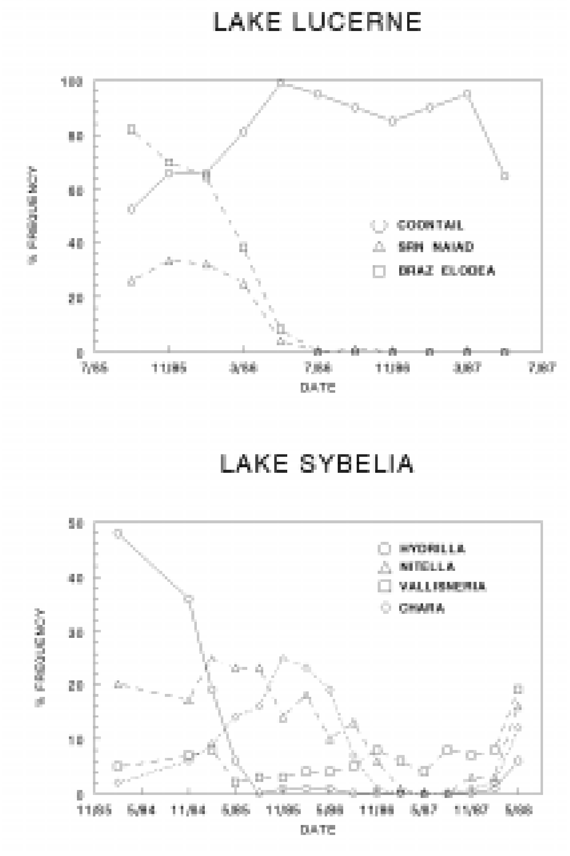

Figure 2. Frequency of occurrence of predominant aquatic plant species in Lakes Lucerne and Sybelia, Florida, stocked with triploid grass carp. Lake Lucerne was stocked in September 1985 (268 fish/ha); Lake sybelia in December 1984 (46 fish/ha). Data modified from Leslie et al. (1987).

preferred species (usually those plants that lake managers wished to remain relatively untouched) are no longer present. Less palatable species can be controlled, but unfortunately only at high stocking rates (Edwards 1974; Vinogradov and Zolotova 1974; Fowler and Robson 1978). A classic example occurred in Deer Point Lake, Florida, where grass carp were stocked to control mixed stands of Eurasian watermilfoil (*Myriophyllum spicatum*) and Illinois pondweed (*Potamogeton illinoensis*) (Van Dyke et al. 1984). The grass carp selectively fed on the pondweed and the marginal emersed flora. After three years, the Eurasian watermilfoil became more abundant than prestocking levels, while the pondweed was eliminated (Fig. 1). Subsequently, all submersed aquatic plants were reduced for a period of six years, and desirable emersed species were also greatly reduced. In 1985, the Eurasian watermilfoil abundance greatly increased and the lake had to be restocked. Repetitions of this scenario in temperate reservoirs in the U. S. may be seen in the accounts of Bates and Webb (1987) for Melton Hill Reservoir (Tennessee), and of Webb (1990) and Wren (1990) for Guntersville Reservoir (Alabama; Table 2).

Examples of selective browsing by grass carp can also be seen in Lakes Clear, Lucerne and Sybelia, Florida (Figs. 1, 2). The target plants in each of these lakes were

Table 2. Synopsis of conditions and results of triploid and diploid grass carp stocking from the literature. Under control level, E=eliminated (all submersed plants), NE=no effects, X=expansion of target plant. Plant codes: hyd=*Hydrilla verticillata*; eda=*Egeria densa*; cdm=*Ceratophyllum demersum*; ngs=*Najas guadalupensis*; msm=*Myriophyllum spicatum*; pis=*Potamogeton illinoensis*; hpa=*Hygrophila polysperma*; naj=*Najas* spp.; cca=*Cabomba caroliniana*; pot=*Potamogeton* spp.; ecs=*Eichhornia crassipes*. Control time is in years.

	lake	fish stocked		submersed	target	vegeta. effects		
Lake	size-ha	/ha	/veg-ha	% cover	plants	level	time	cite
FLORIDA								
Baldwin	80	4	5	80	hyd	NE	3	6
Wildemere	14	7	9	78	hyd	E	0.25	10
Wales	135	12	15	80	hyd	20%	1	5
LL Barton	5	13	14	95	hyd	46%	2	3
LL Barton	5	18	19	95	hyd	25%	1	3
Baldwin	80	25	31	80	hyd	E	2	6
LL Fairview	32	30	43	70	hyd	72%	2	8
Marion	5	30	59	51	ngs	E	0.6	10
Orienta	52	44	98	45	hyd	E	0.5	8
Sybelia	36	47	52	90	hyd	E	0.8	8
Clear (Pasco Co.)	64	50	67	75	hyd	E	1.3	7
Fairy	20	50	54	92	hyd	E	0.6	7
Holden	102	50	83	60	hyd	E	0.9	7
Bell	34	52	60	87	hyd	E	1.3	7
Lucerne	0.8	60	60	100	eda,cdm,ngs	cdm X	0.75	10
Deer Point	1900	61	100	61	msm,pis	msm X	3	7
Clear (Orange Co.)	137	62	100	62	hyd	E	1.2	8
Estelle	24	62			ngs	E	0.25	10
Pineloch	24	62			hyd	E	0.25	10
LL Fairview	32	81	100	81	hyd	E	0.3	8
Molly	6	128			eda	E	0.4	10
Kelly	1	199	205	97	hyd	E	1.25	10
Bailey Canal S	0.4	262			hpa	80%	1	10
Palm	0.7	286	318	90	hyd	E	0.5	10
Bailey Canal N	0.7	286			hpa	E	0.25	10
Burkette	30	363	443	82	hyd	E	0.4	10,11
Martha	12	363	403	90	hyd	E	0.4	10,11
ALABAMA								
Town Creek	160	28	47	60	msm,hyd,naj	msm X	1	13,14
bay in Guntersville	11	28	48	60	"	E		13,15
Coffee Co. Lake	32	74	185	40	lyngbya	88%	3	4
TEXAS								
Conroe	8100	33	75	44	hyd,msm,cdm	E	1	15
ARKANSAS								
Harris Brake	526	6	30	20	cdm,cca,eda	E	1-3	1
Weddington	32	6	30	20	" " "	20%	1-3	1
Overcup	486	7	35	20	" " "	E	1-4	1
Atkins	304	9	36	25	" " "	E	1-4	1
Mallard	121	9	15	60	" " "	E	1-4	1
Pine Bluff	202	10	12	85	" " "	E	1-4	1
Conway	2712	11	28	40	" " "	E	1-4	1
Hurricane	121	14	47	30	" " "	E	1-2	1
Beaverfork	364	15	75	20	" " "	E	1-2	1
Georgia Pacific	658	15	38	40	" " "	E	1-3	1
Calion	259	26	104	25	" " "	E	1-3	1
Halowell	255	26	27	95	" " "	E	1-3	1
Lower White Oak	666	27	135	20	" " "	E	1-3	1
Sugar Loaf	135	29	145	20	" " "	E	1-4	1
Horseshoe	486	38	190	20	" " "	E	1-3	1
Bois d'Arc	304	51	54	95	" " "	E	1-4	1
Bear Creek	324	53	212	25	" " "	E	1-3	1
Des Arc	142	58	290	20	" " "	E	1-5	1
Upper White Oak	417	67	335	20	" " "	20%	1-3	1
Storm Creek	202	85	567	15	" " "	E	1-?	1
Tri County	113	99	330	30	" " "	E	1-4	1
Grampus	81	100	125	80	" " "	E	1-2	1
Hogue	113	140	147	95	" " "	E	1-5	1
TENNESSEE								
Melton Hill	12	56	112	50	msm,ngs,pot	E	2	9
IOWA								
Red Haw	29	27	225	12	pot,cdm,ecs	50-90%	4	2
NEW ZEALAND								
Parkinson	1.9	32	58	55	eda	E	1	12

References: 1=Bailey 1978; 2=Mitzner 1978; 3=Osborne and Sassic 1979; 4=Zolczynski and Smith 1980; 5=Shireman and Maceina 1981; 6=Canfield et al. 1983; 7=Van Dyke et al. 1984; 8=Small et al. 1985; 9=Bates and Webb 1987; 10=Hestand et al. 1987; 11=Leslie et al. 1987;12=Tanner et al. 1990; 13=Webb 1990; 14=Wren 1990; 15=Maceina et al. 1991.

highly palatable for grass carp. Compare these results with those in Deer Point Lake (Fig. 1). In Clear Lake, common coontail (*Ceratophyllum demersum*) remained relatively untouched until hydrilla (*Hydrilla verticillata*) was greatly reduced. In Lake Lucerne, the Brazilian elodea and southern naiad (*Najas guadalupensis*) declined while common coontail increased. The Brazilian elodea declined most quickly, and then southern naiad; without competition, common coontail became more abundant than before stocking. In Lake Sybelia, hydrilla was preferred and nearly eliminated from the lake while the macro-alga chara (*Chara sp.*) initially increased and then declined.

Food preference is a crucial factor in plant management with grass carp. If the target plant is not highly preferred by the grass carp, as happened at Deer Point Lake, then control can be obtained only at stocking rates that will eliminate most nontarget species first and also likely damage the emersed flora. If lower stocking rates are used, grass carp browsing of more palatable species may accelerate spread of the less palatable target plant. Also, it is important to verify food preferences from site to site to avoid surprises. Differences in water chemistry can affect the palatability of plant species to grass carp. In New Zealand studies, grass carp (3 kg size) repeatedly rejected Brazilian elodea from Western Springs but would eat plants of this species collected from the Waikato River (Chapman and Coffey 1971; Table 1).

STOCKING RATES

Grass carp, as they have been used over the past 20 years, have been referred to as an all-or-none proposition for plant control (Allen and Wattendorf 1987). Perusal of Table 2 illustrates that stocking rates as low as 6 fish/ha are known to have removed all submersed plants in temperate lakes as far north as Arkansas. The consequences of overstocking grass carp can be dramatic--all submersed plants were eliminated and emersed species greatly reduced (>60 percent less frequent on transects) in three central Florida lakes (Lakes Bell, Clear and Holden) that initially contained dense infestations of hydrilla (Van Dyke et al. 1984; Leslie et al. 1987; Table 3). The impact has been long term (for more than 15 years); the only plants remaining in these lakes have been in very shallow water (probably inaccessible for large grass carp), or are woody plants such as water primrose (*Ludwigia octovalis*), or are unpalatable species such as spatterdock (*Nuphar luteum*) and sawgrass (*Cladium jamaicense*). From these data, we infer that if one stocks enough grass carp to reduce or remove a target plant with a large biomass, then the marginal plant community will also be substantially reduced. Stott and Robson (1970), Stott (1977), Fowler and Robson (1978), and Shireman and Maceina (1981) have come to similar conclusions. The elimination of the majority of emersed vegetation has led to increased erosion on the shores of Deer Point Lake and Clear Lake. Similar trends are evident for the triploid grass carp lakes that were overstocked (Tables 2,3; Fig. 2,3; Hestand et al. 1986).

In Florida, common wisdom regards retention of at least 15-20 percent lake area cover with aquatic plants (emersed and/or submersed) as essential to the stability and ecology of naturally vegetated systems. Managing aquatic plants with grass carp to achieve this goal has been elusive, but the results in Lake Conway, Florida, have indicated that it is possible. This 702 hectare central Florida lake was stocked with 10 female diploid grass carp/ha (<2 fish per/tonne total vegetation) in September 1977 (Fig. 4). The results over 15 years of monitoring suggest that a desirable balance may have been achieved. Schardt and Nall

Table 3. Annual means for selected water quality variables for four diploid grass carp lakes (modified from Leslie et al. 1983; 1987) and four triploid grass carp lakes. Data for lakes Bell, Clear and Holden (sampled from March 1975 to September 1978) were combined because of identical target plants and sampling design. Data for lakes Martha and Burkette were combined for similar reasons. Means in a row followed by the same letter are not significantly different, Duncans Multiple Range Test (p=0.05). Asterisk (*) indicates year grass carp were stocked (September 1974 in Bell, Clear and Holden); (s) indicates the year the herbicide SONAR-AS (fluridone) was applied in Fish and Live Oak Lake.

	LAKES BELL, CLEAR AND HOLDEN				
	1976	1977	1978	1978	1983
KN ppb	851a	895a	995b	1083b	880a
TP ppb	27a	21b	30ab	36c	35c
TURB ppm	3.2a	4.4b	6.2c	7.1d	6.3c
CHL ppb	32a	26b	28ab	25b	31a
VEG %	59a	10b	3c	3c	3c

		DEER POINT LAKE			
		1976*	1977	1978	1979
KN ppb		320a	260b	570c	520c
TP ppb		19a	12b	13b	18a
TURB ppm		3.1a	3.4ab	3.7a	5.0c
CHL ppb		18a	7b	6b	7b
VEG %	pot	23a	14b	2c	0c
	msm	31a	29a	42b	27a

	LAKES MARTHA AND BURKETTE			
	1980 1981	1981 1982	1985* 1986	1986 1987
KN ppb	498a	635b	647b	884c
TP ppb	26a	23a	47b	60c
TURB ppm	3.4a	2.3b	6.7c	11.3d
CHL ppb	16a	7b	24c	31d
COLOR	9a	10a	35b	26c
VEG %	90a	90a	6b	6b

	LIVE OAK LAKE					FISH LAKE				
	1987* 1988s	1988 1989	1989 1990	1990 1991	1991 1992	1987 1988*s	1988 1989	1989 1990	1990 1991	1991 1992
KN ppb	460a	590b	420a	410a	410a	970a	980a	800b	620c	740bc
TP ppb	15bc	28a	16c	21abc	25ab	51a	59a	46ab	32b	48a
TURB ppm	4.3c	7.9a	3.9c	5.7b	4.8bc	8.3ab	10.0a	7.3b	7.6b	5.7c
CHL ppb	2c	10a	9ab	5b	10a	15c	25ab	18bc	16bc	38a
COLOR	13b	16b	16b	8c	27a	34b	34b	30b	20c	78a
HYD %	95a	75b	88ab	87ab	30c	68a	16b	3bc	3bc	62a
HYD g/m^2	776a	28b	106c	74c	1d	290a	3b	0b	0b	2b

KN=total kjeldahl nitrogen; TP=total phosphorus; TURB=turbidity SiO_2; CHL=chlorophyll a; COLOR=true color (platinum-cobalt units); VEG=total vegetation cover; pis=*Potamogeton illinoensis*; msm=*Myriophyllum spicatum*.

(1981) reported near elimination of hydrilla throughout the Lake Conway system by the end of the second poststocking year (Fig. 4). After hydrilla and Illinois pondweed began to decline, the less palatable eelgrass (*Vallisneria americana*) began to increase in most areas of the lake. Sutton (1977) reported similar results in small ponds in Fort Lauderdale, Florida. Eelgrass, the macro-alga nitella (*Nitella sp.*), and emersed grasses have been maintained while grass carp apparently prevented major reinfestation by the aggressive exotic hydrilla.

Integrated approaches are being evaluated where low stocking rates are used in combination with target-plant reduction by mechanical or chemical methods as suggested by Sutton (1977) and Shireman and Maceina (1981). Lakes Fish and Live Oak in central

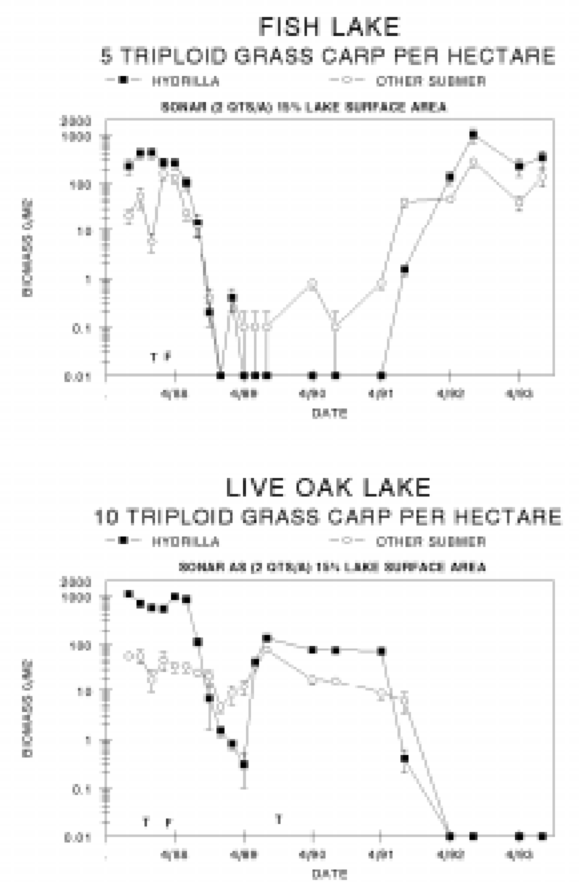

Figure 3. Submersed aquatic plant biomass (g/m^2; n=60) in Fish and Live Oak Lakes, Florida. Fish Lake was stocked with triploid grass carp (5 fish/ha) January 1988; Live Oak Lake stocked with triploid grass carp October 1987 (2.5 fish/ha) and October 1989 (7.5 fish/ha). Fifteen percent of the surface area of each lake was treated with SONAS-AS (fluridone) in early spring 1988.

Florida, were stocked with 5 and 2.5 triploid grass carp/ha respectively, and then 15% of the lake area was treated with the aquatic herbicide SONAR-AS (fluridone). The fluridone treatment virtually eliminated hydrilla in both lakes (Fig. 3). Hydrilla is sensitive to fluridone at low rates (10-15% label rate). Additionally, fluridone treatments at low rates in early spring minimize damage to less sensitive non-target flora. In Fish Lake, hydrilla returned in the fish exclosure but remained undetectable in the lake for three years. Hydrilla has regrown in the fifth year. Field trials indicate that unlike diploids, triploid grass carp plant control efficacy may be relatively short-lived (three to four years). In Live Oak Lake, 2.5 fish/ha were unable to prevent hydrilla reinfestation after initial reduction by fluridone. Hatchery monitoring revealed that 40% mortality had occurred in this group of grass carp, critically reducing an already marginal stocking density. An additional 7.5 fish/ha were added and these were able to maintain hydrilla at approximately 10-20% of its former biomass for two years (Fig. 3). However, hydrilla and other submersed plants in Live Oak Lake have remained nearly eliminated since spring 1992, after an influx of highly colored water.

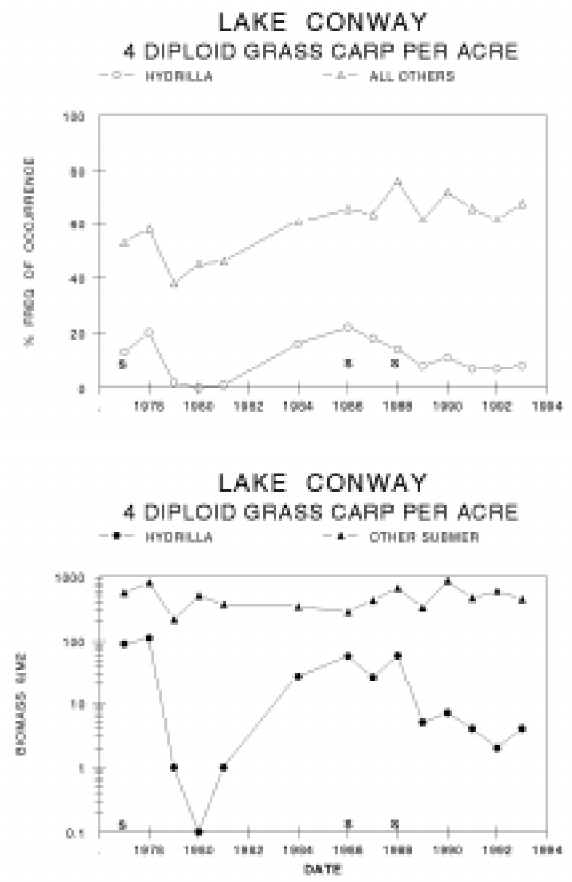

Figure 4. Percent frequency of occurrence and biomass of aquatic plants collected in the Lake Conway chain (East, West, Middle, and South pools), Florida. Sixty random samples were collected in each pool in late summer each year. 6,888 monosex (female) grass carp were stocked in September 1977 (1629 in South Pool; 3408 in Middle Pool; 919 in East Pool; and 1066 in West Pool). In December 1986 and 1988, 1600 and 1000 triploid grass carp, respectively, were stocked into East and West pools.

Thus even at low stocking rates, the potential still exists for the complete elimination of submersed aquatic macrophytes. For example, submersed vegetation may be eliminated if some natural or human induced event reduces aquatic plant biomass directly or reduces growth rates to a level below grass carp consumption rates. Mill Dam, Florida, was stocked in 1987 and 1988 with about 6 fish/ha to control hydrilla (Canfield and Hoyer 1992). In 1985, the percent area covered with macrophytes was 27% (Canfield and Joyce 1985). Aquatic plant abundance remained relatively stable until 1990 when drought reduced the surface area of Mill Dam by about 40%; samples in May 1991 showed no submersed macrophytes at all (Canfield and Hoyer 1992). The duration of these episodes where submersed plants are eliminated is related to the grass carp stocking rate. With triploid grass carp in Fish Lake (5 fish/ha), the duration was nearly three years; with diploid grass carp in Bell Lake (52 fish/ha), the duration has been over 15 years. This is a matter of some concern. Monitoring should continue in Live Oak Lake and Mill Dam to determine plant recovery rates after ambient conditions (water color and level) return to baseline. It is important to remember, however, low stocking rates of grass carp still reduces potential damage to the emersed flora under these circumstances.

Table 4. Average annual water temperatures and results of grass carp browsing in selected lakes in the United States and New Zealand. Under results column, msm= Eurasian watermilfoil.

waterbody	avg water temperature C	number of fish per hectare	vegetation change
Red Haw Lake, Iowa	**13.9**	**27**	**50-90% reduction**
Lake Parkinson, New Zealand	**16.9**	**32**	**submersed elim.**
Mallard Lake, Arkansas		**9**	**submersed elim.**
Guntersville Res., Alabama	**17.5**	**28**	**msm expands, other submersed elim.**
Devils Lake, Oregon	**19.1**	**98**	**Proposed**
Deer Point, Florida	**20.7**	**61**	**msm reduced after other submersed elim.**

Bonar et al. (1987a,b) were concerned that because the Pacific Northwest U. S. is climatologically more like Northern Europe, using the same low stocking rates applied in the south may be inappropriate. At the same time, their goal was to understand how to reduce, not eliminate aquatic plants (Pauley et al. 1987). Grass carp are poikilotherms and thus consume less vegetation at lower temperatures. However, growth rates of plants are also temperature dependent. Data for selected lakes in Table 4 illustrate results of grass carp browsing at various densities and average annual temperatures. These results indicate grass carp overgrazing occurred at a fraction of the Northern Europe stocking rates reviewed by Bonar et al. (1987a,b). Bailey (1978) stated that rates of 25 fish/ha will eliminate submersed plants within two years in Arkansas; experience there showed plants were removed as expected or sooner. Thus, even in the northern U. S., it would seem prudent to begin field trials at no more than 10 grass carp/ha if total elimination of submersed plants is undesirable.

We found that stocking rates of 5 to 6 triploid grass carp/ha have the potential to eliminate palatable submersed plants for several years in sub-tropical and south-temperate lakes when stocked on low biomass levels of plants (100 g/m2 or less). Caution--such low stocking rates will enhance spread of non-palatable plant species. Stocking rates as low as 28 triploid grass carp/ha have eliminated the non-palatable Eurasian watermilfoil after removal of all other submersed species of plants.

EFFECTS ON WATER QUALITY

Changes in aquatic plant communities directly affect other aspects of lake ecology (Boyd 1971). It is known that removal of aquatic macrophytes from a system can increase phytoplankton production (Fitzgerald 1969; Mulligan 1969; Boyd 1971; Wile 1978). Prowse (1971) and Stanley (1974) suggested that consumption of macrophytes and deposition of grass carp fecal matter may further enhance phytoplankton production because aquatic macrophytes repress phytoplankton either by limiting nutrient availability or by allelopathy (Fitzgerald 1969; Boyd 1971; Carter and Hestand 1977). Furthermore, as submersed communities of aquatic plants decline, nutrients from runoff or other sources would further enrich the water column because of the resulting decrease in foliar uptake of these nutrients (Mickle and Wetzel 1978a,b), especially if the marginal emersed flora have also been reduced.

Compared with aquarium studies (e.g., Stanley 1974) and studies where plant communities were controlled with herbicides, early field studies with grass carp have found moderate, if any, increases in nutrient concentrations, and no change or decreases in primary production (planktonic) or chlorophyll α concentrations (Lembi et al. 1978; Rottman and Anderson 1978; Mitzner 1979). Long-term studies in Lakes Bell, Clear, Holden, and Deer Point, Florida, found that after total elimination of the submersed flora, chlorophyll α concentrations declined and required several years to recover; turbidity increased (perhaps due to increased vulnerability of shorelines and sediments to wave action and currents); and nutrients increased modestly in the water column (Table 3; Leslie et al. 1983). Increases in nutrients and turbidity were also found in Lakes Martha, Burkette, Fish, and Live Oak after being stocked with triploid grass carp (Table 3). Conversely, we found chlorophyll α concentrations increased after triploid grass carp eliminated hydrilla in these lakes (Table 3). The increases were modest and similar to those that Richard et al. (1984) and Canfield et al. (1983) found following the introduction of grass carp into several other Florida lakes. In general, enrichment of the water column as a result of the feeding activity of grass carp does not occur to the degree reported after herbicide treatments by Daniel (1972), Buck et al. (1975), Hestand and Carter (1978), and von Zon (1979). Daniel (1972) reported over a thirty-fold increase in available phosphorus, and Hestand and Carter (1978) reported large phosphorus increases and phytoplankton blooms when plants disintegrate after herbicide applications. Biological aquatic plant removal by grass carp occurs over a longer time period, resulting in lower short-term nutrient concentrations in the water column than would be expected using chemical control methods alone. Half of the nutrients in ingested plant material is assimilated by grass carp. The egested half is in the form of a bolus that sinks quickly, or a soluble nutrient fraction that is subject to adsorption to particulate organics and hydrosoil and to assimilation by other biota.

Canfield and Hoyer (1992) show that for lakes supporting abundant growths of aquatic macrophytes (>40% area cover), the removal of aquatic macrophytes will ultimately lead to increases in some trophic-state parameters (e.g. total phosphorus, total nitrogen, and chlorophyll α) and to decreases in Secchi transparency. Such changes are not considered peculiar to the use of grass carp; similar changes occur when other macrophyte management techniques, such as aquatic herbicides, are used (see Buck et al. 1975; Carter and Hestand 1977). The changes also are within ranges that would be expected based on nutrient loading rates and lake morphology (see Shireman et al. 1985). The grass carp lakes are also at the trophic levels that would be predicted based on their regional geology (see Canfield and Hoyer 1988; 1992). The removal of aquatic macrophytes results in a functional and structural shift to a phytoplankton-based ecosystem (Canfield et al. 1983).

EFFECTS ON FISHERIES

Perhaps the most controversial of issues concerning vegetation management with grass carp relate to possible effects on high-profile sportfish and game waterfowl. The controversy is complicated not only by conflicting reports of grass carp impacts but also by the conflicting reports of ecological relationships of aquatic plants to game fish production; in contrast, the importance of vegetation for game waterfowl seems relatively well established (see next section). That habitat complexity in the aquatic environment, expressed as density of aquatic plants or non-living structure, can affect fish community structure is well documented in the literature (Crowder and Cooper 1979; Savino and Stein 1982; Durocher et al. 1984; Bettoli et al. 1992, 1993). The problem occurs when the focus is narrowed to consider only certain game fishes--some of these cut-and-dried relationships blur. It is well known that very high production of fishes can be obtained with little structure at all (Canfield and Hoyer 1992; Lee and Jones 1992), and some experts believe that when lake trophic state is accounted for, relationships of harvestable game fish standing crop to aquatic plant density all but disappear (Hoyer et al. 1985; Canfield and Hoyer 1992). Because grass carp do not compete directly with native North American fishes for food, the effects of grass carp on fisheries can logically be expected to be indirect impacts resulting from habitat alteration and physical disturbance.

Bailey (1978) reported no consistent trends in total standing crop, shad biomass, number of catchable largemouth bass (*Micropterus salmoides*), sunfish (*Lepomis spp.*), crappie (*Pomoxis spp.*), and young-of-the-year sunfish and largemouth bass for 31 Arkansas lakes stocked with grass carp. Other data available on the effects of grass carp on fisheries also show inconsistent trends. Ware and Gasaway (1976) reported a deleterious effect on fish populations in two Florida ponds. But a number of pond culture studies have shown that grass carp increase production of some fishes (Crowder and Snow 1969; Prowse 1971; Johnson and Lawrence 1973). On the other hand, Opuszynski (1979) suggested that grass carp destroyed spawning grounds for some fishes by eliminating vegetation. Grass carp do release nutrients contained in vegetation, thus making them more available for use by other fauna and flora of the system. With grass carp, it may be possible to regulate the flow of nutrients contained in plants so that they are released over a longer period of time versus rapid release from herbicide-killed vegetation (Sutton 1977).

Stanley et al. (1978) reported that fish populations generally increase where grass carp are present. Partial vegetation removal provides a favorable balance of nutrients for food chains of commercial species, and low stocking rates of grass carp can increase commercial production of common carp (*Cyprinus carpio*). Shireman and Maceina (1981) found that while aquatic vegetation is important for maintenance of sportfish (Ware and Gasaway 1976; Miley et al. 1979), the amount of vegetation for maximum production is undetermined. Hinkle (1986) reviewed literature dealing with fisheries and vegetation and concluded that aquatic plants should be managed at a level between 10 and 40 percent cover to maintain a high sustained yield of harvestable sportfish. Colle and Shireman (1980) believe that complete elimination of hydrilla or other macrophytes would probably be detrimental to sportfish communities. These authors found that hydrilla cover in excess of 30 percent resulted in low condition (fatness) of larger (>250 mm total length) largemouth bass, but that smaller bass had high condition and good growth until cover exceeded 50 percent. Bluegill (*Lepomis macrochirus*) and redear sunfish (*L. microlophus*) condition was influenced more by the amount of plant material in the water column than by percent aerial cover. Their condition factors were not affected until near total water-column (78 percent cover and 23 percent surface matted) occupation by vegetation. Canfield and Hoyer (1992) found that none of the measures of aquatic plant abundance measured for Florida lakes were significantly correlated to either total or harvestable fish biomass as estimated by rotenone sampling; no relationship was found between plant area covered and standing stocks of harvestable largemouth bass ($\geq$ 250 mm total length). However, some of their data did suggest that long-term removal of aquatic macrophytes, especially by grass carp, may increase the probability of depressed game fish populations.

The above review on macrophyte abundance related to sport fish production indicates that some very basic ecological interrelationships are not well understood; however, some generalities do emerge. Grass carp eat plants, thus they will impact phytophilous fish species and invertebrates (Canfield and Hoyer 1992; Bettoli et al. 1993). These authors assure us that complete removal of aquatic vegetation reduces but does not eliminate phytophilous fishes. Open water predators, like largemouth bass, seem to do well with or without plants or other structure present; however, poor largemouth bass populations, in Florida, are more likely to occur when plant cover is less than 15 percent or greater than 85 percent (Canfield and Hoyer 1992). Care should be exercised when using grass carp to manage plants in waters with a northern pike (*Esox lucius*) fishery. Aquatic vegetation is critical to several stages of the life history of northern pike (Holland and Huston 1984). After nearly twenty years, it still seems advisable to follow the advice of Boyd (1971) and Strange et al. (1975) that plants should be managed, not eradicated; a balance between rooted plants and phytoplankton is desirable in most systems. A 15-30 percent cover with aquatic plants in lakes and reservoirs seems to be an advisable target until better ecological data become available.

EFFECTS ON WATERFOWL

Several southeastern workers have demonstrated the importance of aquatic vegetation to waterfowl. Florschutz (1972) found that Eurasian watermilfoil, as well as several other species of macrophytes, were being heavily used by waterfowl in North Carolina and Virginia. Duke and Chabreck (1976) classified common coontail, eelgrass, and several species of pondweeds (*Potamogeton spp.*), among others, as important waterfowl food plants in Louisiana. Kerwin and Webb (1971) found that southern naiad was the most important food for dabbling ducks and watershield (*Brasenia schreberi*) most important for diving ducks. Watershield and floating heart (*Nymphoides aquaticum*) are considered good waterfowl foods in Florida (Chamberlain 1960). Krapu (1974) found a high occurrence of spikerush (*Eleocharis spp.*) in waterfowl diets. Montegut et al. (1976) found hydrilla heavily utilized in Lake Wales, Florida. Aquatic plants also provide important habitat for macroinvertebrate communities that are vital as food for waterfowl (Moyle 1961; Arner et al. 1968). A growing body of evidence indicates that hydrilla provides good forage habitat for wintering waterfowl (Johnson and Montalbano 1987).

Because grass carp can severely reduce aquatic plants, especially submersed species, it is assumed that grass carp will have a negative impact on waterfowl. Gasaway and Drda (1976) found that the quality of waterfowl habitat deteriorated in three of four small Florida lakes after grass carp were introduced. Because of ongoing wetland destruction and degradation, waterfowl managers have noted an increased utilization of hydrilla habitats. The growth habit of hydrilla (dioecious form) simulates the shallow marsh habitats that are being rapidly lost in Florida and the rest of the U. S. Johnson and Montalbano (1987) recommend that waterfowl values attributable to plants targeted for plant control be considered and adequately weighed in plant management plans. We do not recommend use of grass carp in areas managed for waterfowl.

AQUATIC PLANT MANAGEMENT USING GRASS CARP

Only the sterile triploid grass carp should be used for aquatic plant management in lakes and large impoundments, and only in areas with legitimate aquatic plant problems. Barriers to prevent escapement of this highly mobile fish are a must, especially for impoundments. Barriers prevent not only loss of efficacy, but also prevent the possibility of negative offsite impacts.

There is a growing trend of stocking grass carp in large impoundments without containment and without adequate regard for valuable fish and wildlife habitat that may be at risk upstream or downstream. In South Carolina, Lake Marion has been stocked with 300,000 triploid grass carp. Downstream lies the Sante National Wildlife Refuge. Dams restrict but do not preclude movement of 120,000 grass carp in Alabama's Guntersville Reservoir, upstream from Wheeler National Wildlife Refuge (David Webb, Tennessee Valley Authority, pers. comm. to JVD). Freshwater wildlife habitats are not the only valuable systems that have been placed in jeopardy. A disturbing scenario may be unfolding in Texas where, far downstream from Lake Conroe, viable grass carp eggs have been found in the Trinity River and where, transplanted smooth cordgrass (*Spartina alterniflora*) only survives in fenced exclosures in parts of the Galveston Bay complex. There is an intensive research effort in this area to determine if there are links between estuarine habitat loss and the presence of escaped grass carp from legal and illegal stockings, but the situation is ominous (Mark Webb, pers comm. to JVD). At the current level of knowledge, stocking grass carp without containment upstream of wildlife refuges and estuaries can only be viewed as environmentally irresponsible.

In determining the suitability of a lake for grass carp, it is essential to first take sufficient steps to reduce nutrient pollution and promote normal water level fluctuation. Aquatic plants flourish where normally dynamic water levels have been stabilized for flood control or other purposes.

Secondly, one must consider the relative value of the lake for fisheries, waterfowl, recreation, and potable water supply and the impact of aquatic plants on these functions. For example, an important waterfowl area is not a suitable candidate for aquatic plant control with the grass carp; the maintenance of boat trails using herbicides or mechanical harvesters would be more appropriate.

Thirdly, the aquatic plant community should be surveyed in mid- to late summer to identify and quantify (with biomass samples if possible) the plant species present. Because the goal is to use the grass carp in multi-use systems to manage nuisance submersed species without severely reducing desirable plant species, the target plant(s) must be more palatable to the grass carp than the desirable plant species. Fortunately, hydrilla (in Florida) is highly preferred by this very selective fish. However, Eurasian watermilfoil is not, and lakes containing this species are generally not suitable candidates (unless virtual elimination of all aquatic plant species is an acceptable scenario).

It is important to integrate a low stocking rate of grass carp with other aquatic plant control methods (Sutton 1977; Shireman and Maceina 1981; Leslie et al. 1987). Because grass carp are difficult and expensive to recapture in significant numbers after release, excessive grazing of vegetation can easily occur and is difficult to remedy. The best approach is to first stock a low density of triploid grass carp (< 10/ha), then reduce the biomass of the target aquatic plants with herbicides or some other method (e.g. mechanical harvesting or drawdown). The major objective is to stock grass carp while plant abundance is high to reduce predation, allow acclimation, and establish a feeding history on the target plant. Then the idea is to greatly reduce the plant biomass with which these herbivores must contend with. To avoid significant mortality from predation, a common cause of control failure, the grass carp stocked should be 40 cm total length (Shireman et al. 1978b; Sutton and Vandiver 1986); however, survival rate is apparently adequate with 300 mm total length fish.

Vegetation removal using grass carp, particularly at a low stocking rate, can proceed slowly, so patience or supplemental aquatic plant management efforts are often required. When used alone, the effects of grass carp may not be apparent for several years after stocking, but the plant reduction may persist for a decade. Integrated approaches have the virtue of providing quick relief. Ascertaining the proper stocking rate for a given situation is still somewhat an empirical exercise and stocking rates (and food preferences) need to be verified regionally. Our experience suggests that it is better to underestimate the stocking rate, provide supplemental plant control as needed, and/or slowly increase the stocking rate until the desired results are obtained.

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