Review of Fish Habitat Improvement Methods for Freshwater Reservoirs

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Fluctuating reservoirs and other impounded waters often have very little structure and aquatic vegetation, especially in older reservoirs in which woody debris present at inundation is long gone. Artificial habitats can provide additional substrate for epibiota as well as cover for ambush predators, fry and fingerlings, and aquatic invertebrates. Artificial habitats can also help congregate fish to improve angling (Bohnsack et al. 1997). Adding substrates for spawning can also augment target species if spawning habitat is limiting (Fitzsimons 1996). Sowing grass on exposed reservoir slopes or adding certain aquatic species of vegetation to reservoirs that have not had the opportunity for colonization can also improve habitat (Smart et al. 1996; Ratcliff et al. 2009).

There is a substantial body of literature on artificial reefs for marine environments. While the marine literature will not be reviewed in detail, some of the issues, principles, and lessons learned from the marine environment are applicable to freshwater. The marine artificial reef literature is largely in proceedings from five international meetings held regularly since 1974 (Clark et al. 1974; Buckley et al. 1985; Seaman et al. 1989; Grove and Wilson 1994; Sako and Nakamura 1995) and in a special sessions by the American Fisheries Society and others (e.g., see special issue of Fisheries 22(4) 1997 and Nakamura et al. 1991). Bibliographies (Steimle and Stone 1973; Stanton et al. 1985; Berger 1993) and books on the topic also exist (D'Itri 1985; Seaman and Sprague 1991).

This review will summarize the literature on freshwater habitat improvements, with a focus on reservoirs, which typically have fluctuating water levels and very little cover or vegetation. The first section will review habitat improvement methods and structures that have been used in past and present efforts, including aquatic vegetation and grass bed treatments. Other sections discuss future research needs and some of the management issues to consider when doing habitat improvement. These include location considerations, attraction versus production, differences among species in artificial habitat use, and seasonal use of structures.

Habitat Structures

Rock— Materials for habitat have largely been materials of convenience, economics, and availability. One of the most basic and durable materials is rock. Rocks may be placed singly, in a pile, in long reefs, in wood cribs, or in scuttled boats (Grove et al. 1991). In Lake Erie, 3,000 metric tons of broken sandstone were used to make twelve 1-2 m high rock piles at 12.2 m depth; Kelch et al. (1999) concluded these were too small and needed to be connected, larger in profile, and shallower. Further additions of 10,900 metric tons of clean rock, brick rubble, and waste concrete created additional reefs that were long strips (243-457 m) 2-4 m tall in 8.5 m of water (Kelch et al. 1999). The reef has attracted fish (smallmouth bass, yellow perch, freshwater drum, white bass, white perch, and channel catfish) and anglers, as well as sport divers. There were 20-50 times more fish at the reef than at control sites. In Lake Michigan, a large limestone reef in 7.6-15.2 m of water was constructed to attract fish for boat anglers (Binkowski 1985). A separate reef was created for shore-based anglers at the South Shore Park Marina for about US$4,000. For the reef bed, sand and pebble-sized beach stone covered about 11,400 m^2, on which football sized field stone was superimposed. The larger stone was piled in 3 long lines about 14.5 m long and 2 m wide and 1.5 m high, which eventually were connected to create a large 'M' shape. The reef attracted a large number of different species including large yellow perch. In a study by Liston et al. (1985), yellow perch were more common around a rock jetty than in Lake Michigan proper, though other species (e.g., round whitefish, lake trout, and alewives) were as diverse or more abundant in Lake Michigan. Largemouth bass juveniles used rocks (~20 mm diameter) placed from the conservation pool shoreline to about 1 m depth (Jackson et al. 2000). The use of the rocks by age-0 largemouth bass did not differ between a continuous patch 20 m long and three intermittent patches of 6.6 m or between steep slope (1 m depth at ≤4.5 m from shore) and shallow slope (1 m depth at ≥ 9 m from shore) sites.

Rocks can also provide spawning habitat. For example, screened gravel and cobble at 0-3 m on areas receiving frequent wave action improved walleye spawning (Bassett 1994). Katt et al. (2011) also noted adult walleye abundance and egg density increased following the addition of cobble to Sherman Reservoir, Nebraska. Geiling et al. (1996) however, found that the majority of spawning habitat projects in Ontario, Canada, failed to augment walleye populations. Smallmouth bass habitat was improved by use of gravel in wooden boxes where spawning habitat was lacking (Bassett 1994). In 11 lakes in Mississippi, every space of 40 gravel beds, consisting of 3.8-6.1 m^3 of gravel, was used by adult bluegill for spawning (Brown 1986). Lake trout have also benefited from added rock in several Great Lakes where patches of spawning habitat of 6 to 18,000 m^2 have been created at depths of 1.8-12 m (Foster and Kennedy 1995; Kevern et al. 1985; Fitzsimons 1996). Other species such as yellow perch, alewife, spottail shiner, slimy sculpin, round whitefish, lake whitefish, and johnny darter have as also spawned on artificial rock reefs (Rutecki et al. 1985). Fitzsimons (1996) and Prevost (1956) suggested the best substrate size for lake trout appears to be 10-20 cm and is angular to sub-angular. Gannon et al. (1985)

suggested using a mix of rock sizes (including large boulders >1 m in diameter) when creating artificial reefs to mimic natural habitat observed in Lake Ontario.

Wood— Another common material is wood, e.g., branches, logs, pallets, and discarded Christmas trees. One of the first evaluations of habitat enhancement in the U.S. found higher numbers of fish around brush piles than in control sites (Rodeheffer 1939). Burress (1961) noted that in timbered areas of Bull Shoals Lake, Missouri, anglers harvested 3,054 lb/acre compared to 113 lb/ac in the remainder of the census area. Davis and Hughes (1971) similarly observed that timbered areas of Bussey Lake, Louisiana attracted more largemouth bass and black crappie, but gar, bullheads, and buffalo preferred open areas. Bryant (1992) compared three different aggregation methods for brush bundles: dense (35 m row 4 m wide), continuous open center (brush stems oriented to the center of the long row, creating a corridor), or discrete open center (several circles of brush with stem toward the center); Age-0 bass increased at all sites, but were more common in the discrete center formation. Adult bass were also more likely to be found there as well.

Moring et al. (1989) used pulp-wood logs to attract fish. Cofer (1991) compared largemouth bass, sunfish and crappie abundance between sunken cedar and oak trees in a study pond. There was no significant difference between tree types in catches of adult largemouth bass. Large crappie tended to be more abundant and sunfish less abundant in oak tree habitat, but the difference was not significant for crappie. Cedars tended to have smaller interstitial spaces favored by juvenile sunfish. Hardwoods such as oak last longer before decomposing, but also can snag more lures (Cofer 1991). Mabbott (1991) noted that evergreen trees had a lifespan of about 4-7 year in Idaho reservoirs, whereas stumps lasted about 20-25 years. Bassett (1994) surveyed Eastern Region national forests in the US and reported that between 1978-1991 about 4,290 fish habitat structures (mostly grouped evergreen trees, wooden pallets, brush piles, log cribs, stumps and whole trees) had been installed in lakes. Half-logs located over suitable gravel spawning sites improved smallmouth bass habitat (Bassett 1994; Wills et al. 2004). The use of wood structures by centrarchids and yellow perch was greatest at 3-6 m, but juvenile and adult centrarchids used trees in water as shallow as 1 m (Bassett 1994). Log cribs with brush held more fish than cribs without added structure; assemblages of log cribs also held more fish than individual cribs (Figure 1; Bassett 1994). Evergreen trees provide a dense cover that is readily used by a variety of centrarchids, yellow perch, and channel catfish (Bolding et al. 2004). Day (1983) reported yellow perch using evergreen trees for spawning. Evergreen trees also led to fewer snags with fishing gear than brush piles (Bolding et al. 2004). A comparison of cedar tree brush piles

Figure 1. Log crib with brush added

(4 trees, 2-2.5 m tall, anchored to concrete blocks) with polypropylene units (2.6 x 4 cm zinc base with 7 polypropylene strands; 1 module had a mix of fifty 1.2-,1.8-, and 2.4-m strands) indicated brush piles attracted more fish (78%), than the polypropylene modules (17%) or control areas (5%; Rold et al. 1996).

Stake beds— Stake beds are fish attractors made of 1.0-1.5 m shafts of wood strips (2 x 5 cm) nailed upright into a rectangular wood frame base (Petit 1972; Mathews 1975; Figure 2). Alternatively, strips can be cemented into concrete blocks or buckets or driven directly into the substrate as well (Figure 3). Stake beds were first evaluated in Kentucky Lake, Tennessee in 1968 where catch per unit effort at the stake beds was nearly five times that of the lake average (Mathews 1975). Stake beds concentrated crappie and other game fish in coves in two Tennessee study reservoirs, but catch rates were still greater in natural cover areas of the reservoirs (Mathews 1975).

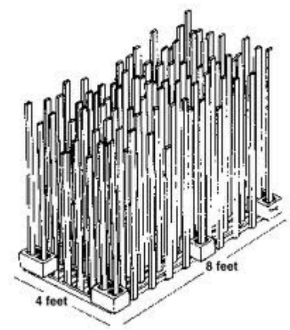

Figure 2. Stake bed.

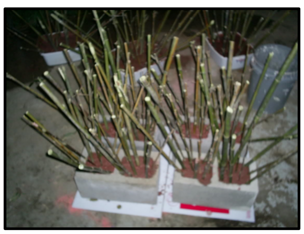

Figure 3. Stake bed in concrete blocks

Comparisons of stake beds with brush piles or evergreen trees indicate that the stake beds are more costly and attract fewer fish (Wege and Anderson 1979; Johnson and Lynch 1992; Bolding et al. 2004).

Commercially available structures— A number of different designs are now available from commercial sources. The **Fish Hab™** is crate-like structure, about 1.2 m square, designed to fit under docks and piers (Figure 4). They are made from recycled plastic and fishing line and can be enhanced by adding brush to the center. Barwick et al. (2004) found that anglers at piers with the Fish Hab had higher catch rates than those at control sites. There is also a string version of the Fish Hab, made of individual plastic strands anchored by weights. Fish Habs are manufactured by Berkley (Berkley Environmental Projects, Spirit Lake, IA) and cost $75 each.

Figure 4. The 'FishHab'

The **AquaCrib®** looks like a big milk crate with a solid panel floor, and openings on the sides (Figure 5). It has a solid hinged lid to provide shade and opens to allow addition of concrete blocks and brush for weighting and added habitat complexity. It is about 1.2 m wide X 1.5 m long X 1.2 m high, made of corrugated plastic (Corrulite) that is designed to support epibiota. It is available from Great Lakes Products for US$100 to $138, depending on quantity (http://www.aquacrib.com/price.html). Wills et al. (2004) found no significant attraction to AquaCribs in four reservoirs of the Au Sable River, Michigan.

Figure 5. The 'AquaCrib'

The **Reef Ball™** is a semi-spherical concrete structure with multiple openings, hollow center, and open top (see Figure 6). Over a half million reef balls have been deployed worldwide, principally in marine environments (see www.reefball.com). Available molds range in size from about 3 kg to 5,000 kg (Derbyshire 2006). They are durable, have a natural appearance, provide cover from predators, and enhance productivity (Derbyshire 2006). Streamers and cement blocks can be added to increase habitat complexity (Sherman et al. 2002). Reef Balls are made by pouring concrete into a fiberglass mold containing a central Polyform buoy surrounded by various sized inflatable balls to make holes. Molds can be leased, bought, or one can pay a per use fee. Prices for molds range from US$719 to $11,489, cost increasing with size.

Figure 6. 'Reef Balls' in situ.

Fish 'N Trees ® are made of flat plastic leaves in a whorl around a central stem to form an underwater 'tree' (Figure 7). The leaves rotate freely around the stem and provide cover for ambush predators. The stems are modular and can be connected to create taller structures (Uberuaga and Bizios 1991). The Fish 'N Tree was invented by Dr. Loren Hill, University of Oklahoma and were produced and marketed by Plastic Research and Development Corporation, Arkansas (Forbis 1991). A call to the company in June 2012 indicated that they are no longer available. The plastic leaves may sag when covered with epibiota or silt and are prone to vandalism (Derbyshire 2006).

Figure 7. The 'Fish 'N Tree'

The **Sphere™** is also commercially available. A 'Cedars Bill Dance Porcupine Fish Attractor Spheres 3 Pack' provides three 15 cm diameter balls to which 1/2 inch PVC pipe is added for US$46 (Figure 8). Richards (1997) compared the sphere to evergreen tree structures and found that, although both attracted black crappie and largemouth bass, trees attracted more young-of-year fish and provided higher angling success (18.9 fish/h versus 9.8 fish/h).

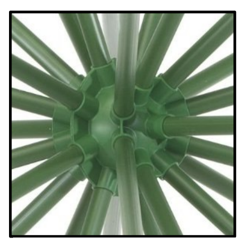

Figure 8. Close-up of The 'Sphere' core

Figure 9. Part for Mossback Rack

Other structures available commercially are the **Mossback Rack** (US$615 for 3 posts, laterals, and base), **Honey Hole Shrub** (US$ 115 ea.) and **Honey Hole Tree** (US$129 ea.; Figures 9, 10). The Mossback Rack is a montage of 3 posts with short lateral projections perpendicular to the post. The Honey Hole structures are designed to minimize lure hang-ups.

Figure 10. Honey Hole Shrub and Honey Hole Tree

Figure 11. The 'Cradle'

Figure 12. The'Safehouse'

The **Cradle** (right) and **Safehouse** (left) are available from www.keystonehatcheries.com for $52 each. These structures are made from reclaimed PVC siding scraps set in a concrete base. The Cradle stands 0.66 m tall and opens to about a 1.07 m diameter, weighs 4.5 kg and has a 20 cm diameter base. It has dozens of fine limbs, ranging from 46 to 66 cm tall and has approximately 1.115 m^2 of surface area. The Safehouse has a surface area of about 4.088 m^2. A similar structure to the Safehouse ($120, 2-pack)and pvc stakebeds ($150, 4-pack) are also available through fishiding.com. To date, no scientific data on the performance of the commercial structures is available.

AquaMats® are foam core sheets with most of the sheet cut into ribbons (Figure 13). The mats come in two basic forms, sinking or floating, in which the ribbons on the sheet either float or sink. The portion of the sheet in which there are no ribbons has a sleeve sewn to allow insertion of metal rods for weighting to the bottom or for suspension from the surface. The ribbons provide a large surface area for epibiota. The mats can be twisted and oriented to make just about any design desired. A section costs $59 each at www.keystonehatcheries.com. They are manufactured by Meridian Aquatic Technology, Calverton, MD (www.aquamats.com). A study by Arndt et al. (2002) found no improvement in rainbow trout growth in a hatchery raceway application, although a transitory benefit in fin condition was observed.

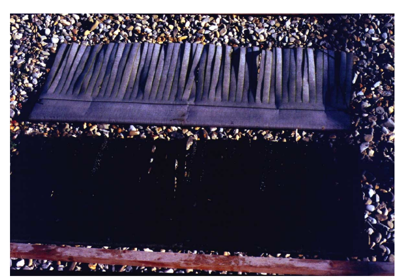

Figure 13. the AquaMat

Snow fence structures and Magic Mushrooms— **Bass Bungalows** are open cylinders constructed of black perforated plastic snow fencing that is wrapped and cured around three 4-cm diameter support rings (polyethylene drain pipe) (Rogers and Bergersen 1999). The structure is oriented horizontally and either weighted down with a block or rock or tied to a frame. Bass Bungalows were designed to provide cover for bass fry. A **Crappie Condo** is a 0.5 m diameter plastic snow fence tube on end (1.2 m tall) with a plastic hat covering the top which provides shaping and protection from predator entry (Figure 14). Galvanized fence stays provide vertical support and a cement block provides anchoring. Modules are clustered in groups to form more complex habitat. The Crappie Condo was an innovation by Gary Bell, U.S. Forest Service, and developed on a habitat improvement project at Saguaro Lake, Arizona (Forbis 1991). The **Magic Mushroom** simulates a lily pad and provides overhead cover. The Magic Mushroom is constructed from a plastic 'hat' similar to that used on the Crappie Condo. Flotation is placed under the hat, and a cable or rope is used to set the distance the hat floats from an anchor at the bottom. The Magic Mushroom and the Bass Bungalows were also developed on the Saguaro Lake project (Forbis 1991).

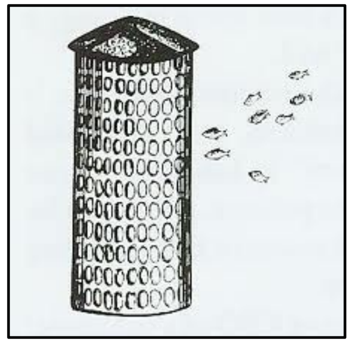

Figure 14. 'Crappie Condo'

For the Saguaro Lake project, nearly 33,000 structures were added to 11 areas of the lake (Uberuaga and Bizios 1991). In Lake Havasu, Nevada an estimated 5,200 crappie condos, 3,300 Fish-N-Trees, 530 bass bungalows, 270 catfish minnow high rises, 80 flathead flophouses, and 40 special spawning structures have been added to improve shore fishing at limited access points (http://www.blm.gov/volunteer/feature/1998/az/index.html); this was a cooperative effort between the Bureau of Land Management and volunteers started in 1993. No data on the artificial habitat effects on fishing success were reported. Rogers and Bergersen (1999) evaluated several different artificial habitat structures (Fish 'N Trees, Bass Bungalows, Crappie Condos, Magic Mushrooms) in two Colorado reservoirs. Although only 40% of the structures tested were Fish 'N Trees, two-thirds of the largemouth bass caught were associated with that structure. Northern pike were not attracted to any of the structures tested (Rogers and Bergersen 1999).

Tubes and pipes— Pipe sections of PVC or concrete blocks can provide cover (Crumpton and Wilbur 1974; Wilbur 1978). If one end of a pipe is plugged, these 'catfish condos' can provide spawning sites for a variety of catfish species. In a study of channel catfish behavior, Brown et al. (1970) observed that juvenile fish used similar habitats as well; the fish preferred the largest volume habitat available (18.9 L), since the fish were schooling. PVC pipe has also been used to create triangular tent-shaped structures that provide some cover and minimize snagging (www.georgiawildlife.com/node/208). PVC pipe was also used to create vertical reef structures that increased local fish densities of the coast of Sweden (Wilhelmsson et al. 2006).

Other materials and designs— Polypropylene rope has been used to create artificial habitat that simulates aquatic macrophytes (Ratcliff et al. 2009). In a study by Santos et al. (2011), polypropylene rope was tied to 1 m^2 PVC frame which had 16 equidistant points (in the same plane as the bottom) from which vertical pipes 1-m tall arose, each with eight strands of unwound rope; Yellow perch, *Rutilus rutilus*, and *Abramis brama* were significantly more abundant in the artificial macrophytes than in rocky shores and sandy beaches.

Coal ash is a waste product from burning coal for energy production. It has been combined with water, flue-gas desulfurization scrubber sludge, and unspecified binders and compressed under pressure to make blocks used as reef material off Long Island, New York (Woodhead et al. 1985; Stone 1982). Coal ash combined with crushed glass can also be used in a concrete mixture or fired at high temperature to create hard, durable products that could be used for artificial habitat (Rawlings et al. 2006).

There is a wide variety of other designs that have been used in the marine reef realm, especially in Japan, where, by 1982, reef building efforts resulted in over 6,000 artificial reefs (Grove and Sonu 1985; Grove et al. 1991). Some of these designs are targeted at particular species such as lobster or abalone. Floating structures, typically marked by buoys and anchored to the bottom, can also attract fish at various depths that remain constant as water levels fluctuate (Reeves et al. 1977; Santos et al. 2008).

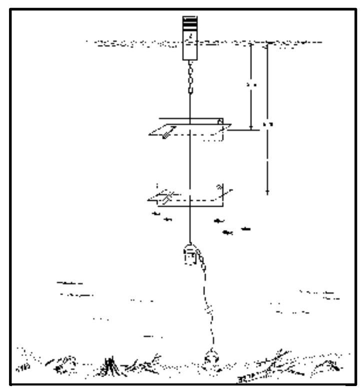
Figure 2. Floating habitat structure (Reeves et al. 1977)

Natural vegetation and grass bed treatments— Grass bed treatments involve planting grasses such as barley on exposed banks of reservoirs after drawdown. Hulsey (1959) planted rye in Arkansas reservoirs in late September. In Kansas reservoirs, Groen and Schroeder (1978) used rye (*Secale* sp., 34-68 kg/ha), rye-grass (*Lolium* sp. , 11 kg/ha), or wheat (*Triticum* sp., 34-68 kg/ha), planted during September or October. In drawdowns before August, Japanese millet (*Echinochloa* sp.) and hybrid sudan-sorghum were planted in Kansas and Arkansas, leading to lush stands (Groen and Schroeder 1978). However, summer drought conditions can lead to poor survival (Plosky 1986). Strange et al. (1982) planted rye, fescue, a sudan-sudan hybrid, and a sudan x sorghum hybrid (49 kg/ha) from July to September on the exposed banks of Lake Nottely, GA at a cost of about US$38/ha; half the plots were fertilized (100 kg/ha).

All grasses grew poorly in unfertilized sites. The numbers of aquatic insects and small sunfish were higher in seeded areas, as well as black bass young-of-year. Fescue and rye seeded in September (35 kg/ha) survived better than the other grasses, producing about 50 stems/m^2 (Strange et al. 1982; Plosky 1986). Northern pike reproduction was observed in a Kansas reservoir when water rose, inundating short grass prairie dominated by buffalo grass (*Buchloe dactyloides*) and blue grama (*Bouteloua gracilis*) (Groen and Schroeder 1978). Winter wheat and barley were both used in a project on Pine Flat Reservoir on the Kings River in California and grew well (Beal et al. 2010; www.krfmp.org/reservoir_habitat.html). While planting can be labor intensive, Ratcliff et al. (2009) observed that juvenile black bass abundance was 54 times higher in planted grass beds and 230 times higher in artificial grass beds (rope and Astroturf®). Higher numbers of cladocerans and higher benthic invertebrate biomass in the artificial beds may have been a factor in the difference between habitat types. One labor-saving method employed by the Tennessee Valley Authority(TVA) was the use of hydro-seeding technology, mounted on a barge (Fowler and Maddox 1974); Japanese millet worked better with the hydro-seeding effort than common buckwheat (*Fagopyrum esculentum*) or ryegrass (*Lolium multiflorum*), forming seed heads within 45 days. A hydro-seeding boat was built by the TVA specifically for use in reservoir bank seeding; an air cushion boat with a 12 V broadcast seeder on the stern also was employed (Fowler and Hammer 1976). Helicopters proved to be more efficient than hydro-seeding or seeding by airboat, allowing coverage of 60-81 ha/hr at a cost of about US$13.81/ha (Fowler and Hammer 1976); a specially designed hopper was used to deliver a maximum payload of about 136 kg per trip. However, hydro-seeding worked better for steeper slopes where water helped adhesion of the seed and led to quicker germination.

Fertilization was recommended in several studies for grain germination and growth (Fowler and Maddox 1974; Strange et al. 1982; Ratcliff et al. 2009), which may be an issue for eutrophic reservoirs or oligotrophic waters where landowners value water clarity. On the other hand, decomposing vegetation can help precipitate colloidal clays, improving water clarity, which in turn can improve predation success (Groen and Schroeder 1978). Grass has a short life, decomposing within one month in Shasta Lake (20-25°C; Ratcliff et al. 2009). A growth study by Ratcliff (2006) indicated that black bass held in an enclosure with grass did not grow significantly larger than those in control sites, suggesting grass serves a greater role as cover for juveniles than food production. In an analysis of Florida lakes with varying amounts of aquatic macrophytes, Maceina (1996) noted that young-of-year densities of largemouth bass increased logarithmically up to about 20-30% vegetated cover; densities leveled out at higher cover percentages. Miranda and Hubbard (1994) similarly observed increased survival of age-0 largemouth bass with the provision of brush shelters (0, 10, 16 or 26% of pond surface area) in experimental ponds;

survival in the smallest size class jumped from 10% in control ponds with predators to 47% in ponds with 26% cover. Durocher et al. (1984) observed a linear relationship between aquatic vegetation and the number of largemouth bass growing to a harvestable size, up to 20% of total lake area.

Native aquatic vegetation in reservoirs is often lacking, due to both high fluctuations in water levels and lack of propagules for colonization. Aquatic plants support higher fish densities, reduce the risk of predation, and provide habitat for species that are reliant on structure (Savino and Stein 1982; Dibble et al. 1996). Ecologically, established native aquatic plant communities can also help prevent invasion of aquatic weed species (Smart et al. 1994). Strakosh et al. (2005) evaluated the ability of American water willow *Justicia americana* to withstand water fluctuations. Plants were inundated for 2 to 8 weeks at depths of 0.75, 1.5, or 2.25 m; drying durations of 2 to 8 weeks were also evaluated. The willow generally survived desiccation (5% died overall), but even 2 weeks of inundation led to 40% mortality across all depth treatments. Smart et al. (1996) suggested a variety (*N* = 10 species) of aquatic plants to consider for propagation, including annuals such as *Chara* sp., *Potamogeton pusillus*, and *Najas* sp., as well as perennials such as *Potamogeton nodosus* (American pondweed), *Vallisneria americana* (American eelgrass), and *Elodea* sp. In shallow Mississippi Delta lakes, *Eleocharis quadrangulata latifolia* (squarestem spikerush) and *Sagitataria latifolia* (arrowhead) had greater coverage and a lower probability of extinction compared to *Nelumbo lutea* (American lotus) and *Eleocharis obtusa* (blunt spikerush; Smiley and Dibble 2006). However, blunt spikerush had a higher stem density than American lotus or arrowhead (Smiley and Dibble 2006). For establishment, peat-potted stock or transfer of tubers is recommended (Smart et al. 1996). Hammer (1992), Doyle and Smart (1993), and Smart et al. (1998) also provide guidance on establishing aquatic macrophytes. Fleming (2010) found that if plants were not kept in exclosures, they disappeared within 2 d after planting in Little Bear Creek Reservoir, Alabama. Fleming (2010) found that propagules survival was in the order *P. nodosus* > *V. americana* > *Potamogeton pectinata*; survival did not vary with planting depths that ranged from 0.3 to 1.0 m. Other projects that have attempted to establish native submergent plants include those at Guntersville Reservoir, AL (Doyle and Smart 1993), El Dorado Lake, KS (Dick and Smart 2004), Arcadia Lake, OK (Dick et al. 2004a), and Cooper Lake, TX (Dick et al. 2004b). On Cooper Lake, Dick et al. (2004b) found that by 'chasing water level', i.e., continuing to plant in hoop cage exclosures as lake levels dropped, they were able to establish founder colonies. A table is given below that lists aquatic plants that have been used for restoration projects in the southern U.S. (Smiley and Dibble 2006); Recommended plants for restoration projects are highlighted in bold.

Table 1. Emergent and submersed plant species evaluated for feasibility of planting in southern U.S. lakes and reservoirs (Smiley and Dibble 2006).

Emergent species

Bacopa monnieri L. Pennell
Echinodorus berteroi (Spreng.) Fassett
Echinodorus cordifolius L. Griseb.
Eleocharis acicularis L. Roemer and Schultes
***Eleocharis palustris* L.** Roemer and Schultes
Eleocharis quadrangulata (Michx.) Roemer and Schultes
Justicia americana L. Vahl
Polygonum hydropiperoides Michx.
Pontederia cordata L.
Sagittaria graminea Michx.
Sagittaria latifolia Willd.
Saururus cernuus L.
Scirpus validus Vahl

Submersed species

Chara vulgaris L.
Brasenia schreberi Gmel.
Ceratophyllum dermersum L.
Elodea canadensis Michx.
Heteranthera dubia (Jacq.)MacM.
Najas guadalupensis (Spreng.) Magnus
Nelumbo lutea Willd.
Nuphar lutea L.
Nymphaea odorata Ait.
Potamogeton illinoensis Morong
Potamogeton nodosus Poir.
Potamogeton pectinatus L.
Potamogeton pusillus L.
Vallisneria americana Michx.
Zannichellia palustris L.

Materials not recommended— Although tires have been used successfully historically (Crumpton and Wilbur 1974; Clady et al. 1979; Smith et al. 1980; Mabbott 1981; Prince et al. 1985) and can increase primary productivity (Prince et al. 1976), they are not recommended due to concerns about petrochemical leaching and aesthetics (Kellough 1991; Day et al. 1993; Derbyshire 2006). Tire bundles have also broken and washed ashore, creating a nuisance (Mathews 1985). Also tires do not provide the habitat complexity offered by alternative structures (Pierce and Hooper 1979; Bolding et al. 2004). This is also true for some other materials used historically such as car bodies, cement blocks, and derelict boats.

Polystyrene can break down over time and be hazardous to fish through ingestion (Derbyshire 2006). Wood treated with chemicals such as creosote and copper napthenate can leach compounds that are harmful to the environment (Derbyshire 2006). Uncured cement can be toxic to invertebrates for up to 12 months due to high pH levels (Lukens and Selberg 2004).

Management Issues

Production versus attraction— Artificial habitats have been shown to improve fishing by concentrating fish (Wilbur 1978; Johnson and Stein 1979; Smith et al. 1980; Bassett 1994), but whether production has increased has been a subject of much debate (Grossman et al. 1997; Lindberg 1997; Bohnsack et al. 1997; Pickering and Whitmarsh 1997). Pardue (1973) observed a linear increase in bluegill production in experimental plastic pools in which the surface area of pine boards ranged from 20 to 100% of total surface area. Randall et al. (1996) noted increased fish production and higher densities of fish in areas of the Great Lakes with vegetation compared to unvegetated sites. Prince et al. (1976) noted increased primary productivity on a tire reef. Tugend et al. (2002) noted two state studies that showed increases in production of age-0 fish as a result of habitat improvement efforts. So evidence and logic suggests that the increased surface area of structures leads to greater primary productivity (assuming the systems not limited by nutrients). However, one of the remaining questions in the debate is the relationship between surface area of artificial habitat for primary production and fish biomass; i.e., how many m^2 is needed to produce another kg of species X? One of the primary concerns in the debate is the possibility of overfishing (Wege and Anderson 1979). While this can be controlled to some degree with regulation, structures concentrate fish which may lead to overfishing. If a fish population is already overharvested, adding structure will just exacerbate the problem (Bolding et al. 2004). Conversely, if forage species are overpopulated and stunted, adding structure will just provide less opportunity for predation and population control (Walters et al. 1991; Bolding et al. 2004).

Location, location, location— The location of artificial structures and habitat is a management decision that must consider a variety of factors. For example, sites exposed to some current help keep sediment from accumulating in interstitial spaces of rock spawning habitat (Herdendorf 1985; Fitzsimons 1995). However, current can cause uneven scour for some artificial reefs, causing the structure to sink or list in soft substrates (Mathews 1985). Harder substrates should be chosen for sites (e.g, if you can sink your hand to your wrist, or further, in the sediment, it is too soft; Mathews 1985). Ease of access for anglers is another variable to consider (Mathews 1985); e.g., structures are placed within casting distance of shore anglers, at accessible shore sites, and/or below piers designed for use by the handicapped. Effects of ice, thermoclines, distance from water intakes and discharges, sediment plumes, boat traffic, and property owner conflicts must also be considered when siting artificial reefs (Kelch et al. 1999). Slope may also be a factor. For example Lynch et al. (1988; cited in Bassett 1994) found that habitat structures sited on steeper slopes (3:1) held more bluegills and provided better angler harvest of bluegill and crappie than those on sites with less slope (25:1).

Depth will also be a consideration, as this affects species use (Walters et al. 1991), creation of potential boating hazards, and access to the structure by shore anglers. Reservoir water level fluctuation will dictate the depth targeted for artificial structures. Reeves et al. (1977) observed Alabama spotted bass and bluegill using structures as deep as 33 m and as far as 250 m from shore. Damage by waves could also affect the depth chosen for a structure; sites should have depths greater than 0.5 x wave height (Mathews 1985). For aquatic plants, which rely on photosynthesis for sustenance, water quality will affect the depth that light can penetrate and the depth chosen for re-vegetation efforts (Dick et al. 2004b). Dick et al. (2004b) suggested depths of 30-120 cm for submersed species, 30-90 cm for floating-leaved species, and 0-30 cm for emergent species.

Have specific objectives— A scattershot approach to habitat improvement could likely lead to wasteful spending and little change in fish and fishing. For example, salmonids tend to be cruisers and did not use artificial habitats (stake beds, brush piles, PVC pipe cage, milk crate cage) provided in an Alaska reservoir (Viavant 1995). In their literature review, Bolding et al. (2004) provided a key to assist in determining the need and type of artificial structure. Projects should have specific objectives, such as attracting fish to portions of a large system so shore anglers can catch more panfish (Uberuaga and Bizios 1991). Projects should target specific species. E.g., brush bundles worked well for largemouth bass and spotted bass, but smallmouth bass showed no preference for them (Vogele and Rainwater 1975). South American cichlids, such as *Geophagus brasiliensis*, *Cichla kelberi* and *Tilapia rendalli*, show affinities for structure that varied with habitat complexity (Santos et al. 2008), whereas species from other families were not attracted to structure.

The interstitial size and depth of the habitat will also have an influence on habitat use. For example, Santos et al. (2008) found that *C. kelberi* was associated with highly complex structures, but moderately complex structures favored *G. brasiliensis; T. randalli* preferred bottom structures over midwater structures. Lynch and Johnson (1989) and Johnson et al. (1988) observed that bluegill preferred small (40 mm) and medium (150 mm) interstice spaces, but when largemouth bass were present, the highest preference was for the smaller space; largemouth bass preferred the medium size to the larger interstice size (350 mm). Walters et al. (1991) compared two interstice sizes (40 and 350 mm) at two depths (3.0 and 4.5 m) in an Ohio reservoir. Bluegill preferred 40 mm interstice at 3 m, whereas pumpkinseed and bullheads preferred the same interstice size at 4.5 m. White crappie showed no preference for either size or depth. Prince et al. (1985) found that sunfishes preferred low profile reefs at depths of about 1.5 m, whereas centrarchid basses preferred high profile reefs in deeper water (4.6-6.1 m).

Seasonal use by species— Use of artificial reefs and structures may vary seasonally (Graham 1992). Rutecki et al. (1985) observed that highest use of an artificial reef in Lake Michigan by yellow perch and alewives was during warmer months (May to October). Rold et al. (1996) also noted more fish (largemouth bass and *Lepomis* sp.) at artificial structures in July and August than in September or October. Similar patterns have been observed by Reeves et al. (1977) and Smith et al. (1980) in Alabama. Walters et al. (1991) and Johnson and Lynch (1992) observed a decline in artificial habitat use by white crappie in midsummer as they moved to deeper water. Drawdowns and thermoclines will also affect use, with fish potentially abandoning structures as water levels change.

Amount of structure to add— Given the cost of habitat improvements, the amount of artificial habitat to add is a key management decision. The costs of projects can be reduced by the use of volunteer labor and by involving multiple agencies and angler organizations (Forbis 1991; Uberuaga and Bizios 1991). However, as the Brevoort Lake (US$350,000; Bassett 1994) and Saguaro Lake (US$2.89 million; Forbis 1991) projects demonstrated, there are still significant costs involved in large scale efforts. Japan has spent millions to billions of dollars, augmenting reefs on 10% of their ocean shelf (Stone 1982; Stone et al. 1991). Nonetheless, for underutilized fisheries, a few structures at appropriate shore access sites can provide significantly higher angler catch rates. In some cases, e.g., where spawning habitat is limiting, the addition of some rock substrate can significantly improve recruitment (Fitzsimons 1996). If an increase in primary production is a goal, a larger reservoir-wide effort will be needed, such as grass-bed treatments, re-vegetation, or investment in large numbers of artificial habitat structures. Data from aquatic vegetation manipulation studies and reviews suggested that about 20-30% vegetated cover was optimal for age-0 largemouth bass survival (Durocher et al. 1984; Dibble et al. 1996; Maceina 1996). This serves as a rough benchmark for other potential habitat projects.

Future research needs

The balance between economic costs and benefits of habitat improvement (e.g., fish production, angler harvest and satisfaction, and license sales) is still a subject for further examination. E.g., would an annual effort at grass bed seeding be more cost effective than a large-scale application of artificial habitat? Another need is the development of a scientifically sound way to estimate the number of artificial structures that are needed to achieve fish abundance objectives or maintain certain catch-per-unit-effort targets. This was similarly noted by Tugend et al. (2002), who suggested more data is needed to assess effects of artificial structures on fish population size and recruitment. The study by Pardue (1973) provided some indication of this relationship in an experimental study in which net production of bluegill was linearly correlated with structure surface area, expressed as a percentage of pond surface area ($Y = 243.34 + 1.408X$, where Y = kg/ha bluegill net production and X = the percent increase in surface area). In this case, a 40% increase in surface area provided about 50-100 kg/ha of bluegill production. Pond- and reservoir-scale testing along similar lines is needed. Better information on the estimated life expectancy and use over time for various structures would also be useful information for planning as well. Changes in use with structure age have been suggested by Graham (1992), who observed differences in seasonal use between older and newer structures. Bortone (1998) has similarly suggested that long term evaluations of habitat improvement projects are needed. The re-vegetation research has primarily been conducted in the Southeast. More work is needed in the western U.S. to determine which native aquatic plant species work for the conditions there. Further research is needed to determine the carrying capacity for various structures for the particular species that use them. E.g., would territorial behavior by a large predator such as largemouth bass limit use of a structure to one fish and what is the size of the territory defended? Would a 'duplex catfish condo' be used by two different fish? What is the minimum size of a structure that would attract a target fish? If I have 100 units of a structure, is the fish production maximized by grouping some of these or by dispersing all of them into individual sites? What is the best distance between structures for various structure types? Following up on the work by Johnson et al. (1988) and Walters et al. (1991), how can artificial habitats be optimized to provide the best size interstices for the target species? Can structures made from waste glass and coal ash be manufactured at a reasonable cost?

Summary

The use of artificial structures can significantly improve fishing by attracting fish to locations that anglers can target. Structures can improve primary production, but more structures are needed for this purpose. The relationship between structure numbers and location and primary production still needs further research. Artificial spawning habitat can also improve abundance of certain species if this habitat is limiting. Inoculating reservoirs with appropriate native aquatic plant species can significantly improve fish habitat and primary production as well as discouraging invasive aquatic plant species. Data for vegetation studies indicates that 20-30% coverage of the pond area is optimal. Fertilization and exclosures will likely be needed to encourage establishment of plants and grass-beds. Before using artificial habitats, multiple factors need to be considered. These include location, the biology of the target species and limiting factors for their abundance, cost, depth, and numbers of structures. Many species, such as salmonids in general, are not attracted to structure in reservoirs, and efforts aimed at these species would be wasted. More research is needed to optimize habitat improvement efforts in reservoirs, but with the knowledge gained to date, significant improvements in fishing and fish production can be made if done properly.

Literature Cited

Arndt, R.E., M.D. Routledge, E.J. Wagner, and R.F. Mellenthin. 2002. The use of AquaMats® to enhance growth and improve fin condition among raceway cultured rainbow trout *Oncorhynchus mykiss* (Walbaum). Aquaculture Research 33:359-367.

Barwick, R.D., T.J. Kwak, R.L. Noble, and D.H. Barwick. 2004. Fish populations associated with habitat-modified piers and natural woody debris in piedmont Carolina reservoirs. North American Journal of Fisheries Management 24:1120-1133.

Bassett, C.E. 1994. Use and evaluation of fish habitat structures in lakes of the eastern United States by the USDA Forest Service. Bulletin of Marine Science 55(2-3):1137-1148.

Beal, B., K. Johnson, L. Long, S. Haugen, C. Lollar, and C. Hanson. 2010. Kings River Fisheries Management Program, Annual Technical Report 2009-2010. www.krfmp.org/reservoir_habitat.html

Berger, 1993. Artificial reef bibliography-a reference guide. Artificial Reef Development Center, Washington, D.C.

Binkowski, F.P. 1985. Utilization of artificial reefs in the inshore areas of Lake Michigan. Pages 349-362 *in* D'Itri, F.M., editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Bohnsack, J.A., A.M. Ecklund, and A.M. Szmant. 1997. Artificial reef research: is there more than the attraction-production issue? Fisheries 22(4):14-16.

Bolding, B., S. Bonar, and M. Divens. 2004. Use of artificial structures to enhance angler benefits in lakes, ponds, and reservoirs: a literature review. Reviews in Fisheries Science 12:75-96.

Bortone, S.A. 1998. Resolving the attraction-production dilemma in artificial reef research: some yeas and nays. Fisheries 23(3):6-10.

Brown, A.M. 1986. Modifying reservoir fish habitat with artificial structures. Pages 98-102 in G.E. Hall and M.J. Vand Den Avyle, editors. Reservoir Fisheries Management: Strategies for the the '80s. Reservoir Committee, Southern Division American Fisheries Society, Bethesda, Maryland.

Brown, B.E., I. Inman, and A. Jearld, Jr. 1970. Schooling and shelter seeking tendencies in fingerling channel catfish. Transactions of the American Fisheries Society 99:540-545.

Bryant, G.J. 1992. Direct observation of largemouth and smallmouth bass in response to various brush structure designs in Ruth Reservoir, California. Fish Habitat Relationship Technical Bulletin No. 10. USDA Forest Service, Pacific Southwest Region.

Buckley, R., J. Grant, and J. Stephens, Jr. 1985. Third international artificial reef conference, 3-5 November 1983, Newport Beach, California. Forward. Bulletin of Marine Science 37(1):1-2.

Burress, R.M. 1961. Fishing pressure and success in areas of flooded standing timber in Bull Shoals Reservoir, Missouri. Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners 15:296-298.

Clady, M.D., R.C. Summerfelt, and R. Tafanelli. 1979. Floating tire breakwaters and ecology of coves in an Oklahoma Reservoir. Proceeding of the Southeastern Association of Fish and Wildlife Agencies 33:495-506.

Clark, W., J. Mosely, and R. Stone. 1974. Proceedings of an international conference on artificial reefs. Report TAMU-SG-74-103. Texas A&M University Sea Grant College, College Station.

Cofer, L.M. 1991. Oak versus cedar trees as fish attractors: comparisons by angling and electrofishing. Pages 67-72 *in* J.L. Cooper and R.H. Hamre, editors. Warmwater Fisheries Symposium I, June 4-8, 1991, Scottsdale, AZ. USDA Forest Service General Technical Report RM-207.

Crumpton, J.E., and R.L. Wilbur. 1974. Florida's fish attractor program. Proceedings of an International Conference on Artificial Reefs. Texas A&M Sea Grant Publication TAMU-SG-74-103, College Station, Texas.

Davis, J.T., and J.S. Hughes. 1971. Effect of standing timber on fish populations and fisherman success in Bussey Lake, Louisiana. Pages 255-264 in G.E. Hall, editor. Reservoir fisheries and limnology. Special Publication 8. American Fisheries Society, Bethesda, Maryland.

Day, R.E. 1983. An evaluation of the addition of artificial spawning substrate on yellow perch reproduction and year class strength in Ferguson Reservoir. Ohio Department of Natural Resources, Division of Wildlife Technical Report F-29-R, Study 13.

Day, K.W. K.E. Holtze, J.L. Metcalfe-Smith, C.T. Bishop, and J.J. Dutka. 1993. Toxicity of leachate from automobile tires to aquatic biota. Chemosphere 27(4):665-675.

Derbyshire, K. 2006. Fisheries guidelines for fish-friendly structures. Department of Primary Industries, Queensland. Fish Habitat Guideline FHG 006. 64 pp.

Dibble, E.D., K.J. Killgore, and S.L. Harrel. 1996. Assessment of fish-plant interactions. American Fisheries Society Symposium 16:357-372.

Dick, G.O., and R.M. Smart. 2004. Aquatic vegetation restoration in El Dorado Lake, Kansas: a case study. U.S. Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility, Report ERDC/EL TR-04-6.

Dick,G.O., R.M. Smart, and E.R. Gilliland. 2004a. Aquatic vegetation restoration in Arcadia Lake, Oklahoma: a case study. U.S. Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility, Report ERDC/EL TR-04-7.

Dick,G.O., R.M. Smart, and J.K. Smith. 2004b. Aquatic vegetation restoration in Cooper Lake, Texas: a case study. U.S. Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility, Report ERDC/EL TR-04-5.

D'Itri, F.M. 1985. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Doyle, R.D., and R.M. Smart. 1993. Potential use of native aquatic plants for long-term control of problem aquatic plants in Guntersville Reservoir, Alabama. Report 2, competitive interactions between beneficial and nuisance species. U.S. Army Corps of Engineers, Waterways Experiment Station Technical Report A-95-6, Vicksburg, Mississippi.

Durocher, P.P., W.C. Provine, and J.E. Kraai. 1984. Relationship between abundance of largemouth bass and submerged vegetation in Texas reservoirs. North American Journal of Fisheries Management 4:84-88.

Fitzsimons, J.D. 1996. The significance of man-made structures for lake trout spawning in the Great Lakes: are they a viable alternative to natural reefs? Canadian Journal of Fisheries and Aquatic Sciences 53(Suppl. 1):142-151.

Fleming, J.P. 2010. Macrophyte re-establishment and deductive GIS modeling to indentify planting locations for fish habitat enhancement projects. Master's Thesis, Mississippi State University, Mississippi.

Forbis, L.A. 1991. The Saguaro Lake project: Doing it right. Pages 357-363 *in* J.L. Cooper and R.H. Hamre, editors. Warmwater Fisheries Symposium I, June 4-8, 1991, Scottsdale, AZ. USDA Forest Service General Technical Report RM-207.

Foster, N.R., and G.W. Kennedy. 1995. Egg deposition by lake trout and lake whitefish at Tawas artificial reef, Lake Huron, 1990-1993. Pages 191-206 *in* M. Munawar, T. Edsall, and J. Leach, editors. The lake trout ecosystem: ecology, fisheries and management. Academic Publishing, New York.

Fowler, D.K., and J.B. Maddox. 1974. Habitat improvement along reservoir inundation zones by barge hydroseeding. Journal of Soil and Water Conservation 29 (6):263-265.

Fowler, D.K., and D.A. Hammer. 1976. Techniques for establishing vegetation on reservoir inundation zones. Journal of Soil and Water Conservation 31(3):116-118.

Gannon, J.E., R.J. Dahehy, J.W. Anderson, G. Merritt, and A.P. Bader. 1985. The ecology of natural shoals in Lake Ontario and their importance to artificial reef development. Pages 113-139 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Geiling, W.D., J.R.M. Kelso, and E. Iwachewski. 1996. Benefits from incremental additions to walleye spawning habitat in the Current River, with reference to habitat modification as a walleye management tool in Ontario. Canadian Journal of Fisheries and Aquatic Sciences 53(Suppl. 1):79-87.

Graham, R.J. 1992. Visually estimating fish density at artificial structures in Lake Anna, Virginia. North American Journal of Fisheries Management 12:204-212.

Groen, C.L., and T.A. Schroeder. 1978. Effects of water level management on walleye and other coolwater fishes in Kansas reservoirs. Pages 278-283 in R.L. Kendall, editor. Selected coolwater fishes of North America. Special Publication 11. American Fisheries Society, Bethesda, Maryland.

Grossman, G.D., G.P. Jones, and W.J. Seaman, Jr. 1997. Do artificial reefs increase regional fish production? A review of existing data. Fisheries 22(4):17-23.

Grove, R.S., and C.J. Sonu. 1985. Fishing reef planning in Japan. Pages 187-251 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Grove, R.S., C.J. Sonu, and M. Nakamura. 1991. Design and engineering of manufactured habitats for fisheries enhancement. Pages 109-152 *in* Seaman, W., Jr., and L.M. Sprague. 1991. Artificial habitats for marine and freshwater fisheries. Academic Press, New York.

Grove, R.S., and C.A. Wilson. 1994. Introduction. Bulletin of Marine Science 55(2-3):265-267.

Hammer, D.A. 1992. Creating freshwater wetlands. Lewis Publishers, Chelsea, Michigan.

Herdendorf, C.E. 1985. Physical and limnological characteristics of natural spawning reefs in western Lake Erie. Pages 149-183 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan

Hulsey, A.H. 1959. A proposal for the management of reservoirs for fisheries. Proceedings of the Southeastern Association of Game and Fish Commissioners 12:132-143.

Jackson, J.R., R.L. Noble, E.R. Irwin, and S.L. Van Horn. 2000. Response of juvenile largemouth bass to habitat enhancement through addition of artificial substrates. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 54:46-58.

Johnson, D.L., R.A. Beaumier, and W.E. Lynch, Jr. 1988. Selection of habitat structure interstice size by bluegills and largemouth bass in ponds. Transactions of the American Fisheries Society 117:171-179.

Johnson, D.L., and W.E. Lynch, Jr. 1992. Panfish use and angler success at evergreen tree brush, and stake-bed structures. North American Journal of Fisheries Management 12:222-229.

Johnson, D.L., and R.A. Stein, editors. 1979. Response of fish to habitat in standing water. American Fisheries Society, North Central Division, Special Publication 6, Bethesda, Maryland.

Katt, J.D., B.C. Peterson, K.D. Koupal, C.W. Schoenebeck, and W.W. Hoback. 2011. Changes in relative abundance of adult walleye and egg density following the addition of walleye spawning habitat in a Midwest irrigation reservoir. Journal of Freshwater Ecology 26(1):51-58.

Kelch, D.O., F.L. Snyder, and J.M. Reutter. 1999. Artificial reefs in Lake Erie: biological impacts of habitat alteration. American Fisheries Society Symposium 22:335-347.

Kellough, R.M. 1991. The effects of scrap automobile tires in water. Waste Management Branch Ontario Ministry of the Environment. Technical Report, Ontario, Canada.

Kevern, N.R, W.E. Beiner, S.R. VanDerLann, and S.D. Cornelius. 1985. Preliminary evaluation of an artificial reef as a fishery management strategy in Lake Michigan. Pages 443-458 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Lindberg, W.J. 1997. Can science resolve the attraction-production issue? Fisheries 22(4):10-13.

Liston, C.R., D.C. Brazo, J.R. Bohr, and J.A. Gulvas. 1985. Abundance and composition of Lake Michigan fishes near rock jetties and a breakwater, with comparisons to fishes in nearby natural habitat. Pages 491-514 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Lukens, R.R., and C. Selberg. 2004. Guidelines for marine artificial reef materials, 2nd edition. Joint publication of the Atlantic and Gulf States Marine Fisheries Commissions, Number 121. http://www.gsmfc.org/pubs/SFRP/Guidelines_for_Marine_Artificial_Reef_Materials_January_2004.pdf

Lynch, W.E., Jr., and D.L. Johnson. 1989. Influences of interstice size, shade, and predators on the use of artificial structures by bluegills. North American Journal of Fisheries Management 9:219-225.

Lynch, W.E., Jr., K.A. Kayle, and D.L. Johnson. 1988. Importance of bottom gradient as an artificial structure placement factor. Appendix III of evaluation of fish management techniques. Project F-57-R Study 10. Ohio Cooperative Fish and Wildlife Research Unit, Ohio State University, Columbus.

Mabbott, L.B. 1991. Artificial habitat for warmwater fish in two reservoirs in southern Idaho. Warmwater Fisheries Symposium, USDA Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-207.

Maceina, M.J. 1996. Largemouth bass abundance and aquatic vegetation in Florida Lakes: an alternative interpretation. Journal of Aquatic Plant Management 34:43-47.

Mathews, H. 1985. Physical and geological aspects of artificial reef site selection. Pages 141-148 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan

Mathews, R.C. Jr. 1975. Dynamics of crappie utilization of stake beds. M.Sc. Thesis, Tennessee Technological University,

Miranda, L.E., and W.D. Hubbard. 1994. Winter survival of Age-0 largemouth bass relative to size, predators, and shelter. North American Journal of Fisheries Management 14:790-796.

Moring, J.R., M.T. Negus, R.D. McCullough, and S.W. Herke. 1989. Large concentrations of submerged pulpwood logs as fish attraction structures in a reservoir. Bulletin of Marine Science 44:609-615.

Nakamura, M., R.S. Grove, and C.J. Sonu, editors. 1991. Recent advances in aquatic habitat technology. Proceedings of the JAPAN-US Symposium on artificial habitats for fisheries, 11-13 June 1991. Nihon University Conference Hall, Tokyo, Japan. International Marine Science and Technology Federation, Tokyo.

Pardue, G.B. 1973. Production response of the bluegill sunfish, *Lepomis macrochirus* Rafinesque, to added attachment surface for fish-food organisms. Transactions of the American Fisheries Society 102:622-626.

Petit, G.D. III. 1972. Stake beds as crappie concentrators. Proceedings of the Southeastern Association of Game and Fish Commissioners 26:401-406.

Pickering, H. and D. Whitmarsh. 1997. Artificial reefs and fisheries exploitation: a review of the 'attraction versus production' debate, the influence of design and its significance for policy. Fisheries Research 31:39-59.

Pierce, B.E., and G.R. Hooper. 1979. Fish standing crop comparisons of tire and brush fish attractors in Barkley Lake, Kentucky. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 33:688-691.

Ploskey, G.E. 1986. Effect of water-level changes on reservoir ecosystems, with implications for fisheries management. Pages 86-97 in G.E. Hall and M.J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the '80s. Southern Division American Fisheries Society, Bethesda, Maryland.

Prevost, G. 1956. Use of artificial and natural spawning beds by lake trout. Transactions of the American Fisheries Society 86:258-260.

Prince, E.D., O.E. Maughan, and P. Brouha. 1985. Summary and update of the Smith Mountain Lake artificial reef project. Pages 401-430 in F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Prince, E.D., R.J. Strange, and G.M. Simmons, Jr. 1976. Preliminary observations on the productivity of periphyton attached to a freshwater artificial tire reef. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 30:207-215.

Randall, R.G., C.K. Minns, V.W. Cairns, and J.E. Moore. 1996. The relationship between an index of fish production and submerged macrophytes and other habitat features at three littoral areas in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 53(Suppl. 1):35-44.

Ratcliff, D.R. 2006. Evaluating the effectiveness of grass bed treatments as habitat for juvenile bass in a drawdown reservoir. Master's Thesis, Utah State University, Logan.

Ratcliff, D.R., W.A. Wurtzbaugh, and J. Zustak. 2009. Evaluating the effectiveness of grassbed treatments as habitat for juvenile black bass in a drawdown reservoir. North American Journal of Fisheries Management 29:1119-1129.

Rawlings, R.D., J.P. Wu, and A.R. Boccaccini. 2006. Glass-ceramics: their production from wastes— a review. Journal of Material Science 41:733-761.

Reeves, W.C., G.R. Hooper, and B.W. Smith. 1977. Preliminary observations of fish attraction to artificial mid-water structures in freshwater. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 31:471-476.

Richards, T.A. 1997. Placement and monitoring of synthetic and evergreen tree fish attracting devices. Massachusetts Division of Fisheries and Wildlife Technical Report, Westborough.

Rodeheffer, I.A. 1939. Experiments in the use of brush shelters by fish in Michigan lakes. Papers of the Michigan Academy of Sciences, Arts, and Letters 24:183-193.

Rogers, K.B., and E.P. Bergersen. 1999. Utility of synthetic structures for concentrating adult northern pike and largemouth bass. North American Journal of Fisheries Management 19:1054-1065.

Rold, R.E., T.S. McComish, and D.E. VanMeter. 1996. A comparison of cedar trees and fabricated polypropylene modules as fish attractors in a strip mine impoundment. North American Journal of Fisheries Management 16:223-227.

Rutecki, T.L., J.A. Dorr III, and D.J. Jude. 1985. Preliminary analysis of colonization and succession of selected algae, invertebrates, and fish on two artificial reefs in inshore southeastern Lake Michigan. Pages 459-489 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.

Sako, H., and M. Nakamura, editors. 1995. ECOSET'95: International conference on ecological system enhancement technology for aquatic environments. Vol. I-III. International Marine Science and Technology Federation, Tokyo.

Santos, L.N., F.G. Araújo, and D.S. Brotto. 2008. Artificial structures as tools for fish habitat rehabilitation in a neotropical reservoir. Aquatic Conservation: Marine and Freshwater Ecosystems 18:896-908.

Santos, L.N., A.A. Agostinho, C. Alcaraz, J. Carol, A.F.GN. Santos, P. Tedesco, E. Garcia-Berthou. 2011. Artificial macrophytes as fish habitat in a Mediterranean reservoir subjected to seasonal water level disturbances. Aquatic Science 73:43-52.

Savino, J.F., and R.A. Stein. 1982. Predator-prey interaction between largemouth bass and bluegills as influenced by simulated, submersed vegetation. Transactions of the American Fisheries Society 111:255-266.

Seaman, W. Jr., R.M. Buckley, and J.J. Polovina. 1989. Advances in knowledge and priorities for research, technology, and management related to artificial aquatic habitats. Bulletin of Marine Science 44(2):527-532.

Seaman, W., Jr., and L.M. Sprague. 1991. Artificial habitats for marine and freshwater fisheries. Academic Press, New York.

Sherman, R.L., D.S. Gilliam, and R.E. Spieler. 2002. Artificial reef design: void space, complexity, and attractants. Journal of Marine Science 59:S196-S200.

Smart, R. M., J. W. Barko, and D. G. McFarland. 1994. "Competition between *Hydrilla verticillata* and *Vallisneria americana* under different environmental conditions," Technical Report A-94-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Smart, R.M., R.D. Doyle, J.D. Madsen, and G.O. Dick. 1996. Establishing native submersed aquatic plant communities for fish habitat. American Fisheries Society Symposium 16:347-356.

Smart, R.M., G.O. Dick, and R.D. Doyle. 1998. Techniques for establishing native aquatic plants. Journal of Aquatic Plant Management 36:44-49.

Smiley, P.C., Jr., and E.D. Dibble. 2006. Evaluating the feasibility of planting aquatic plants in shallow lakes in the Mississippi Delta. Journal of Aquatic Plant Management 44:73-80.

Smith, B.W., G.R. Hooper, and C.S. Lawson. 1980. Observations of fish attraction to improved artificial midwater structures in freshwater. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 34:404-409.

Stanton, G., D. Wilbur, and A. Murray. 1985. Annotated bibliography of artificial reef research. Report 74. Florida Sea Grant College Program, Gainsville.

Steimle, F., and R.B. Stone. 1973. Bibliography on artificial reefs. Coastal Plains Center for Marine Development Services Publication 73-2. Wilmington, North Carolina.

Stone, R.B. 1982. Artificial reefs: toward a new era in fisheries enhancement? Marine Fisheries Review 44:2-3.

Stone, R.B., L.M. Sprague, J.M. McGurrin, and W. Seaman, Jr. 1991. Artificial habitats of the world: synopsis and major trends. Pages 31-60 in W. Seaman, Jr, and L.M. Sprague, editors. Artificial habitats for marine and freshwater fisheries. Academic Press, New York.

Strakosh, T.R., J. L. Eitzmann, K.B. Gido, and C.S. Guy. 2005. The response of water willow *Justicia americana* to different water inundation and desiccation regimes. North American Journal of Fisheries Management 25:1476-1485.

Strange, R.J., W.B. Kittrell, and T.D. Broadbent. 1982. Effects of seeding reservoir fluctuation zones on young-of-the-year black bass and associated species. North American Journal of Fisheries Management 2:307-315.

Tugend, K.I., M.S. Allen, and M. Webb. 2002. Use of artificial habitat structures in U.S. lakes and reservoirs: a survey from the Southern Division AFS Reservoir Committee. Fisheries 27(5):22-27.

Uberuaga, R., and L. Bizios. 1991. Arizona warmwater fisheries enhancement: the Saguaro Lake project. Pages 57-61 *in* J.L. Cooper and R.H. Hamre, editors. Warmwater Fisheries Symposium I, June 4-8, 1991, Scottsdale, AZ. USDA Forest Service General Technical Report RM-207.

Viavant, T. 1995. Fish attraction to artificial structure in Chena Lakes, Alaska. Alaska Department of Fish and Game, Fisheries Data Series No. 95-6, Anchorage.

Vogele, L.E., and W.C. Rainwater. 1975. Use of brush shelters as cover by spawning black basses (*Micropterus*) in Bull Shoals Reservoir. Transactions of the American Fisheries Society 104:264-269.

Walters, D.A., W.E. Lynch, Jr., and D.L. Johnson. 1991. How depth and interstice size of artificial structures influence fish attraction. North American Journal of Fisheries Management 11:319-329.

Wege, G.J., and R.O. Anderson. 1979. Influence of artificial structure on largemouth bass and bluegills in small ponds. Pages 59-69 *in* D.L. Johnson and R.A. Stein, editors. Response of fish to habitat structure in standing water. North Central Division American Fisheries Society Special Publication 6.

Wilbur, R.L. 1978. Two types of fish attractors compared in Lake Tohopekaliga, Florida. Transactions of the American Fisheries Society 107(5):689-695.

Wilhelmsson, D., S.A.S. Yaha, and M.C. Ohman. 2006. Effects of high-relief structures on cold temperate fish assemblages: a field experiment. Marine Biology Research 2:136-147.

Wills, T.C., M.T. Bremigan, and D.B. Hayes. 2004. Variable effects of habitat enhancement structures across species and habitats in Michigan reservoirs. Transactions of the American Fisheries Society 133:399-411.

Woodhead, P.M. J. J.H. Parker, and I.W. Duedall. 1985. The use of by-products from coal combustion for artificial reef construction. Pages 262-282 *in* F.M. D'Itri, editor. Artificial reefs: marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.