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Remedial effectiveness of a pond biomanipulation: Habitat value and concentrations of polychlorinated biphenyls in fish

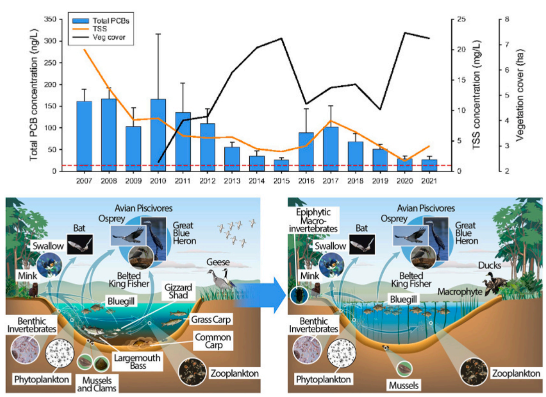
Rebecca A. Efroymson *, Mark J. Peterson [1], R. Trent Jett, Natalie A. Griffiths, Evin T. Carter, Allison M. Fortner, Christopher R. DeRolph, Peijia Ku, Paul G. Matson, Rachel M. Pilla, Teresa J. Mathews

Oak Ridge National Laboratory, Oak Ridge, TN, USA

HIGHLIGHTS

- An ecological manipulation in a contaminated pond reduced PCB concentrations in fish.
- Habitat value metrics were measured over a 15-y period.
- The pond transitioned from gizzard shad and largemouth bass dominance to sunfish.
- PCB concentrations in bluegill decreased below risk-based targets.
- Habitat metrics for most taxa are at least equal to those before biomanipulation.

GRAPHICAL ABSTRACT



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ABSTRACT

The fish and plant communities in a pond contaminated with polychlorinated biphenyls (PCBs) in East Tennessee, USA, were manipulated to reduce ecological and human-health risk associated with exposure to the chemical contaminants. We evaluated the success of the remedial action using a habitat valuation approach, as well as measuring PCB concentrations in fish. Risk reduction objectives included: alter the fish community to favor fish that do not resuspend, bioaccumulate, or biomagnify PCBs; stabilize contaminated sediments to improve water quality; and stabilize shoreline soils and enhance riparian habitat. Fish targeted for removal included gizzard shad, largemouth bass, and nonnative carp. Reduced PCB concentrations in fish have characterized the new bluegill-dominated community, although a weir-overtopping event led to the need for additional removals of gizzard shad and largemouth bass. Sunfish abundance is high, as was intended. Moreover, amphibian and waterbird diversities have increased in the years following biomanipulation, possibly owing to improvements in the riparian zone and increased structural (vegetation) complexity in both the aquatic and terrestrial environment. Thus, the remedial action has improved aspects of habitat value, and PCB concentrations in sunfish

* Correspondence to: P.O. Box 2008, Oak Ridge, TN 37831-6036.
E-mail address: efroymsonra@ornl.gov (R.A. Efroymson).

[1] Deceased

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have dropped below the remediation level (risk-based target value) for this pond (1 μg/g in fish fillets or 2.3 μg/g in whole body fish).

1. Introduction

Biomanipulation, a type of ecological engineering also termed ecomanipulation or ecological enhancement [27], is "the intervention in an ecosystem by manipulating key components of the ecological community" [54] to meet a particular objective. Biomanipulation is based on the theory of trophic cascades, in which alterations (e.g., introductions or removals) of key species can affect the flow of energy and matter through indirect interactions that can control the entire ecosystem [26,62,9]. The objectives of biomanipulations have ranged from reducing cyanobacterial bloom events in ponds and lakes [54] to controlling invasive species and restoring native fish communities [58]. Biomanipulation may also be used as a restoration option to reduce ecological or human-health risks from exposure to chemical contaminants [32].

Biomanipulation may be especially relevant to contaminants that bioaccumulate through the food web. For example, in aquatic ecosystems, aqueous concentrations of bioaccumulative chemicals such as mercury, selenium, and polychlorinated biphenyls (PCBs) are often very low, even when fish tissue concentrations are elevated. Accordingly, state and federal agencies have developed fish-tissue-based water quality criteria [37,57], because the tissue concentrations are more indicative of exposure and risk than aqueous concentrations. Holistic, ecosystem-based strategies such as biomanipulation can mitigate the risks of exposure to bioaccumulative contaminants by altering uptake pathways by biota [32,51].

Chemicals that bioaccumulate in fish also tend to be hydrophobic and, therefore, partition into sediments. Because sediments can serve as a source of hydrophobic contaminants to water and biota long after the original source is gone, the remediation of surface-water bodies contaminated with PCBs typically involves a removal action, i.e., excavation of sediments [19]. However, because dredging can be costly and a significant disturbance to the ecosystem, and because natural attenuation can be slow [33] biomanipulation can be a long-term, effective remedial alternative if the objective is to decrease PCB bioaccumulation in fish [12,49,59].

Assessing habitat attributes can complement measurements of chemical contaminants in environmental media to provide evidence of ecological risk and its reduction. Habitat services include food, shelter, breeding areas, and movement corridors. Habitat value relates to potential population abundance and diversity [29,30], and it indicates what could be harmed if environmental media are excavated to reduce risk from chemical contaminants [8,60]. Thus, habitat valuation is important for prioritizing sites for remediation and selecting remedies, and it could also be important for evaluating remedial effectiveness.

We developed a habitat valuation approach for remedial decision making that uses three broad categories of metrics of habitat value: site use by groups of organisms (e.g., taxa richness), site rarity (e.g., presence of rare communities), and use value added from the spatial context (e.g., presence of habitat corridor) [18]. Here, we use that method to evaluate the effectiveness of a biomanipulation of the K-1007-P1 Pond, a PCB-contaminated water body in East Tennessee, USA. The goal of biomanipulation of the K-1007-P1 Pond was to enhance components of the ecological community and ecosystem that minimize PCB uptake and impede pathways to human and ecological receptors. Thus, we ask: a) has the value of habitat for a range of taxa been maintained or improved since the biomanipulation, and b) have PCB concentrations in fish trended downward since the biomanipulation?

2. Background

2.1. Site description

The nine-hectare K-1007-P1 Pond, adjacent to the main plant area of the U.S. Department of Energy (DOE) East Tennessee Technology Park (ETTP), is fed by stormwater from several ETTP outfalls and a tributary that comes in from a smaller, adjacent pond. It is bordered by a state highway to the southeast, a weir to Poplar Creek and a road to the west, and railroad tracks to the southwest (Fig. SI.1 in supplemental information). The ETTP complex has a 40-yr history (1945–1985) of enriching uranium for defense missions and the commercial nuclear power industry. PCBs were used across the ETTP complex in the 1950–1970s as dielectric fluids for capacitors and transformers and as lubricating oils. Storm drains and sediments in certain areas around the complex remain contaminated with PCBs, and drainage and effluents from ETTP laboratory drains as well as natural runoff caused the K-1007-P1 Pond to be highly contaminated with PCBs.

Prior to remediation, the pond was bordered by a combination of natural and managed areas. A large, mowed, grassy, and often saturated field was situated to the north of the pond. The pond is moderately to steeply sloped on the south side, whereas the north banks and adjacent field are nearly flat. A natural wetland to the southwest is fed by a clear stream that flows from upland areas south of the highway. Narrow, fringe wetlands were present around the pond, especially near the east and north sides, but mowed areas encroached on these wetlands, and mowing was performed adjacent to the pond shore. The pond received high nutrient inputs from Canada geese (*Branta canadensis*) that grazed on the mowed lawn.

2.2. Pre-biomanipulation food web

Prior to biomanipulation, the fish population of the K-1007-P1 Pond contributed to ecosystem conditions that maximized PCB biomagnification. The fish population was dominated by non-native grass carp (*Ctenopharyngodon idella*) and common carp (*Cyprinus carpio*), as well as gizzard shad (*Dorosoma cepedianum*), which resuspend PCB-contaminated sediments and remobilize these hydrophobic contaminants while foraging [13]. The absence of both submerged and emergent, rooted vegetation in the pond resulted in high biomass of suspended algae, flocculent sediments, and open-water conditions that are highly desirable for gizzard shad [13]. Like many planktivorous fish, gizzard shad are high in oily tissue and can accumulate high concentrations of hydrophobic PCBs. The top predator in the K-1007-P1 Pond was the largemouth bass (*Micropterus salmoides*), which feed predominantly on sunfish and juvenile shad. Largemouth bass is a popular recreational fish species, and because of concerns about elevated PCBs, the pond is posted for no fishing.

2.3. Remediation objectives and targets

The reduction of PCB concentrations in fish was a major remediation goal in the engineering evaluation/cost analysis (EE/CA) that compared potential remedial actions for the K-1007-P1 Pond [5]. The baseline human health risk assessment indicated that PCBs in fish from this pond contribute 95% of the incremental lifetime cancer risk (4.1 $\times 10^{-3}$) to a human recreational fisherman receptor from fish consumption. The baseline ecological risk assessment projected that piscivorous wildlife might also be at risk from PCBs in fish (hazard quotient[2] of 9.2 [14]). The risk-based target value (i.e., the remediation level) was set at 1 μg/g PCBs in fish fillets (assumed to be equivalent to 2.3 μg/g PCBs in whole body fish based on [3]), reflecting a) levels shown to be protective of piscivorous wildlife, b) US Food and Drug Administration recommendations, and c) consistency with protective levels for surrounding, contaminated water bodies [14]. Biomanipulation was selected by DOE and endorsed by the U. S. Environmental Protection Agency (EPA) and the Tennessee Department of Environment and Conservation (TDEC) as the option for remediation based on presumed efficacy in meeting the risk-based target values and economic efficiency. Also relevant is the Tennessee water quality criterion for the protection of fish and wildlife (14 ng PCBs/L)[52], though this was not a remediation objective.

Under the biomanipulation, the pond was expected to transition from a hyper-eutrophic environment toward a more mesotrophic environment. Primary producers would shift from phytoplankton to macrophytes and their associated epiphyton (Fig. 1). Greater dominance of macrophytes would help stabilize sediments. Certain fish species would be targeted for removal because they are vectors for PCB transfer, consumers of vegetation with key functions, or upper-trophic-level piscivores (Table 1).

The goal for promoting a new fish community in the K-1007-P1 Pond was to favor fish that do not resuspend, bioaccumulate, or biomagnify PCBs. The removal of common carp and suckers such as buffalo or *Moxostoma* spp. would reduce sediment bioturbation (and PCB redissolution) and increase water clarity, promoting macrophyte growth. The food chain would be shortened, with no top-level predators, and increased dominance of small sunfish, such as bluegill (*Lepomis macrochirus*), which consume terrestrial and aquatic invertebrates. Moreover, small sunfish are not typical table fare and are thus less likely to be consumed by fishers. And generally, macrophyte-dominated ponds offer less desirable opportunities for angling.

The conceptual model for the biomanipulation, which emphasizes component management actions, is depicted in Fig. 2.

3. Methods

3.1. Remediation activities

The biomanipulation in 2009 included draining the pond, removing fish, covering contaminated sediments with clean soil, establishing native vegetation, and restoring a different fish community. One assumption underlying the assertion that biomanipulation would meet risk targets was that PCB inputs would not increase over time. We briefly summarize elements of the remedial action here; details can be found in BJC [6]. Goals and remedial activities are listed in Table 2.

3.1.1. Source control

A clean cover was implemented to control sediments as a source of PCBs to water and aquatic biota. Backfill soil was added to cover the existing sediment to minimize PCB migration and to recontour the pond to create shallow water zones for planting. The pond was drained to allow the soil to be deposited, as well as to facilitate piscicide use (below).

3.1.2. Fish community

Fish community surveys in the pond have been conducted annually in the winter since 2009. Before remediation, surveys were also conducted in 2004 and 2007. Data were collected each year by boat electrofishing in deeper waters, and shorelines were surveyed using backpack electrofishers in 2011–2021. Surveys included collection of all fish in timed electrofishing efforts across the pond. Each fish was identified to species, and length and weight measurements were collected.

In the main remedial action, the fish species targeted for removal included gizzard shad, largemouth bass, grass carp, and common carp, as described above, as well as suckers and buffalo fishes (Catostomidae), catfish (Ictaluridae), and crappie (*Pomoxis* spp.) for the reasons identified in Table 1. A fish piscicide (rotenone) was applied to remove all fish from the pond. This action provided an opportunity to manipulate the fish population without concerns about the presence of high-contaminant-containing fish or undesirable species remaining. Fish were restocked multiple times after rotenone was applied to achieve the desired sunfish-dominated community. Fish stock was collected from both local source streams and hatcheries and, in total, 86,800 hatchery-raised bluegill were added to the pond from 2010 to 2020.

A goal for fish management was to prevent the reintroduction of undesirable fish species into the pond. The most likely mechanism for reintroduction was migration from Poplar Creek during periods of flooding. Although fish barriers were installed, a 2010 flooding event led to a need to remove gizzard shad, threadfin shad (*Dorosoma petenense*), largemouth bass, common carp, and smallmouth buffalo (*Ictiobus bubalus*) from the pond.

3.1.3. Plant community

Another remediation goal was to stabilize pond sediments, including the newly added sediment cap consisting of clean soil. Therefore, aquatic plants native to the region were installed (after recontouring), and plant species were selected based on hardiness, suitability to expected conditions, and growth characteristics, especially depth and density of root masses. Planting depth, density, and arrangement, as well as species planted, are detailed in [15]. Related to this remediation goal was a need to alter habitat for undesirable fish species, such as gizzard shad, which prefer open, pelagic systems where they feed predominantly on phytoplankton and zooplankton. Deeper-water plant species such as American lotus (*Nelumbo lutea*) and fragrant water lily (*Nymphaea odorata*) were added. In total, 14 species of aquatic plants were added to the pond [6], creating a diverse wetland plant community. Vegetation coverage within the pond was quantified by visual interpretation of aerial imagery for 2006 (pre-planting) and 2010 through 2021 (post-planting).

These management actions focused on areas within the pond, but nutrient inputs from the surrounding landscape also needed to be addressed. Riparian zones along the northern boundary of the pond, which were largely mowed fescue fields, were replanted to create a 1.6-ha riparian buffer zone to enhance native habitats and discourage use by Canada geese. Fescue and other non-native plants were removed, and native grasses and forbs were planted with species listed in DOE [15].

3.2. Monitoring contaminants and habitat

3.2.1. PCB analysis

To assess spatial and temporal variability in exposure to PCBs following remediation activities, water samples were collected four times each year (March, June, July, and August) for analysis of aqueous PCB and total suspended solid (TSS) concentrations from the outfall of the K-1007-P1 Pond. In addition, to address uncertainties associated with potential PCB inputs from a storm drain leading to the pond (Storm Drain 100; SD100), samples were collected from SD100 at these same time periods starting in 2018. For PCBs, 2 L of water was collected in certified, clean 1-L amber glass bottles and held in a secure refrigerator until delivery to a subcontract laboratory for analysis of 209 congeners by high-resolution gas chromatography/high-resolution mass spectrometry using EPA method 1668 (U.S. Environmental Protection

[2] A hazard quotient is the quotient of a chemical toxicant concentration in an environmental medium (in this case, concentration in forage fish) divided by a toxicologically effective concentration. A quotient above 1 is considered hazardous.

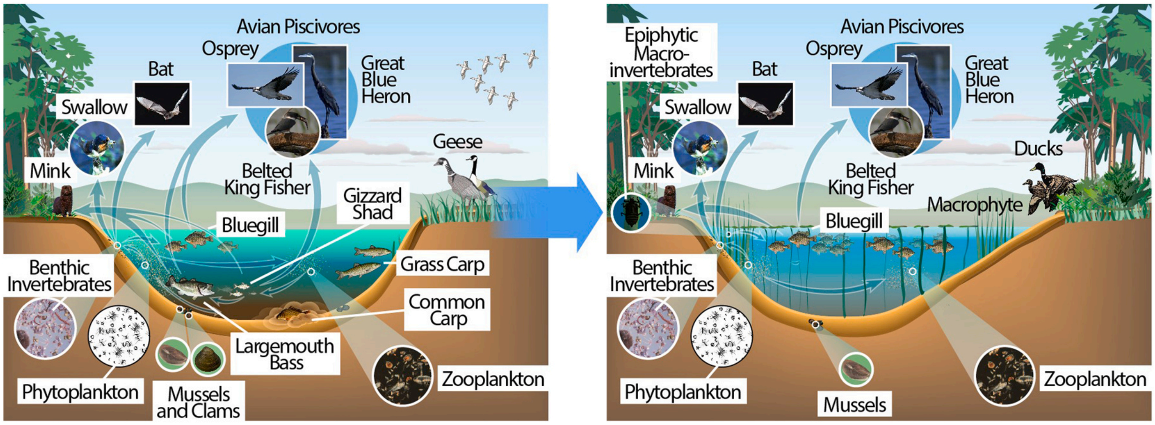

Fig. 1. Conceptual models depicting the pre-biomanipulation (left) and planned post-biomanipulation (right) food webs of the K-1007-P1 Pond. Arrows represent the pathways of PCB contamination from forage or prey to consumers. In the left panel, the predominant aquatic food chains begin with phytoplankton, include benthic and planktonic invertebrates, and end with largemouth bass. In the right panel, the predominant aquatic food chain is from macrophytes to epiphytic invertebrates to bluegill.

Table 1
Fish targeted for removal in biomanipulation of PCB-contaminated K-1007-P1 Pond.

Justification	Taxa[a]
Long-lived species with capacity to reach high PCB levels	Largemouth bass, common carp, grass carp, buffalo, suckers, catfish
Higher trophic level fish that can reach high PCB levels	Largemouth bass, crappie, catfish
Fish that feed on aquatic vegetation, which stabilizes sediments, or that feed on and resuspend sediment detritus [50]	Buffalo, carp (especially grass carp), shad
Fish that are common table fare (to deter fishing)	Largemouth bass, crappie, catfish, large sunfish

[a] shad (*Dorosoma* spp.), grass carp (*Ctenopharyngodon idella*), common carp (*Cyprinus carpio*), buffalo (*Ictiobus* spp.), catfish (*Ictaluridae* spp.), sunfish (*Lepomis* spp.), largemouth bass (*Micropterus salmoides*), crappie (*Pomoxis* spp.).

Agency 2010). TSS samples were collected concurrently with PCB samples in clean 1-L Nalgene bottles and were filtered onto pre-weighed, 0.45 mm glass-fiber filters, which were then dried before weighing again.

To assess the effectiveness of the biomanipulation activities with respect to risk targets, fish were collected annually for PCB analysis. Bluegill sunfish were the target species for performance monitoring, and fillets (n = 20) as well as whole body composites (n = 6 composites, made from 10 fish each) were prepared for analysis. Largemouth bass fillets were measured for PCBs prior to 2009, but the reduced population was not large enough to collect a sample annually after biomanipulation. In 2015 and 2020, newly recruited largemouth bass were of suitable size for a collection, and six fish in each year were collected for PCB analysis.

All fish were collected by boat electrofishing and were processed within 24 h of collection. Each fish was weighed, and its length was measured. Fillets were scaled with the skin on, and whole-body fish were homogenized by a triple pass through a stainless-steel grinder. Samples were stored frozen (−20 °C) until shipment to analytical labs for PCB analysis (EPA method SW846–8082, quantification of Aroclor mixtures by gas chromatography).

3.2.2. Water quality measurements

Water quality was measured in the K-1007-P1 Pond following remediation from 2010 through 2021. Water samples were collected in June, July, and August of each year from three permanent north-to-south-oriented transects. Within each transect, Secchi depth (i.e., water clarity) and near-surface (depth of ~10 cm) temperature, conductivity, dissolved oxygen (DO), and pH, were measured from three locations at distances of about one-third of the pond width for each transect. At each location DO was also measured vertically at 50-cm intervals to assess changes with depth. Turbidity was measured at each near-surface location using a Hach 2100 P portable turbidimeter. Additionally, grab samples of surface water were collected at the two northernmost locations of each transect and analyzed for TSS and nutrient (total phosphorus [TP], soluble reactive phosphorus [SRP], ammonium-N, and nitrate-N) concentrations, and chlorophyll *a* using standard protocols [1].

3.2.3. Habitat value

Most metrics for scoring habitat value were developed in Efroymson et al. [18]. The three types of habitat value metrics related to site use value, site rarity, and use value added from spatial context. Specific metrics of the three types of value are listed in Table SI.1, supplemental information.

Habitat value metrics were scored prior to the biomanipulation (in 2004) and after the biomanipulation (between 2010 and 2021) as high, medium, and low or a range of two levels (e.g., low to medium). The implementation of metrics of habitat value for ponds was guided by: 1) data availability and 2) ease of development of criteria for high, medium, and low habitat value, based on descriptions or statistics from the literature or other reasonable definitions [18]. High habitat value was unusually high, compared to the typical value for the region. Low value was unusually low. Medium habitat value was typical. If regional species abundance data were available for a metric, we chose 25th and 75th percentiles as thresholds for high (>75th), medium (75th to > 25th), and low (<25th) habitat value designations, respectively. Other metrics and scoring criteria were adopted from existing biotic indices (e.g., Reservoir fish assemblage index in Tennessee Valley Authority Impoundments, [35]). Some scoring criteria were based on thresholds for what is atypical for the region [18].

For some measures, qualitative characteristics were assigned to the high, medium, and low based on the possible range of land-cover occurrence data from the Southern Appalachian Man in the Biosphere program (SAMAB) [45]. Cutoffs for high, medium, and low habitat value for abundance of sensitive and rare species were estimated in Efroymson et al. [18] by authors with the appropriate expertise. Also, we assumed the presence of invasive species lowers habitat value relative to the presence of noninvasive, nonnative species, which lowers habitat value relative to the absence of nonnatives.

We estimated habitat value in several spatial contexts: (1) the Oak Ridge Reservation (ORR), which includes DOE buildings and land; (2) the region around the ORR defined by areas that have been sampled

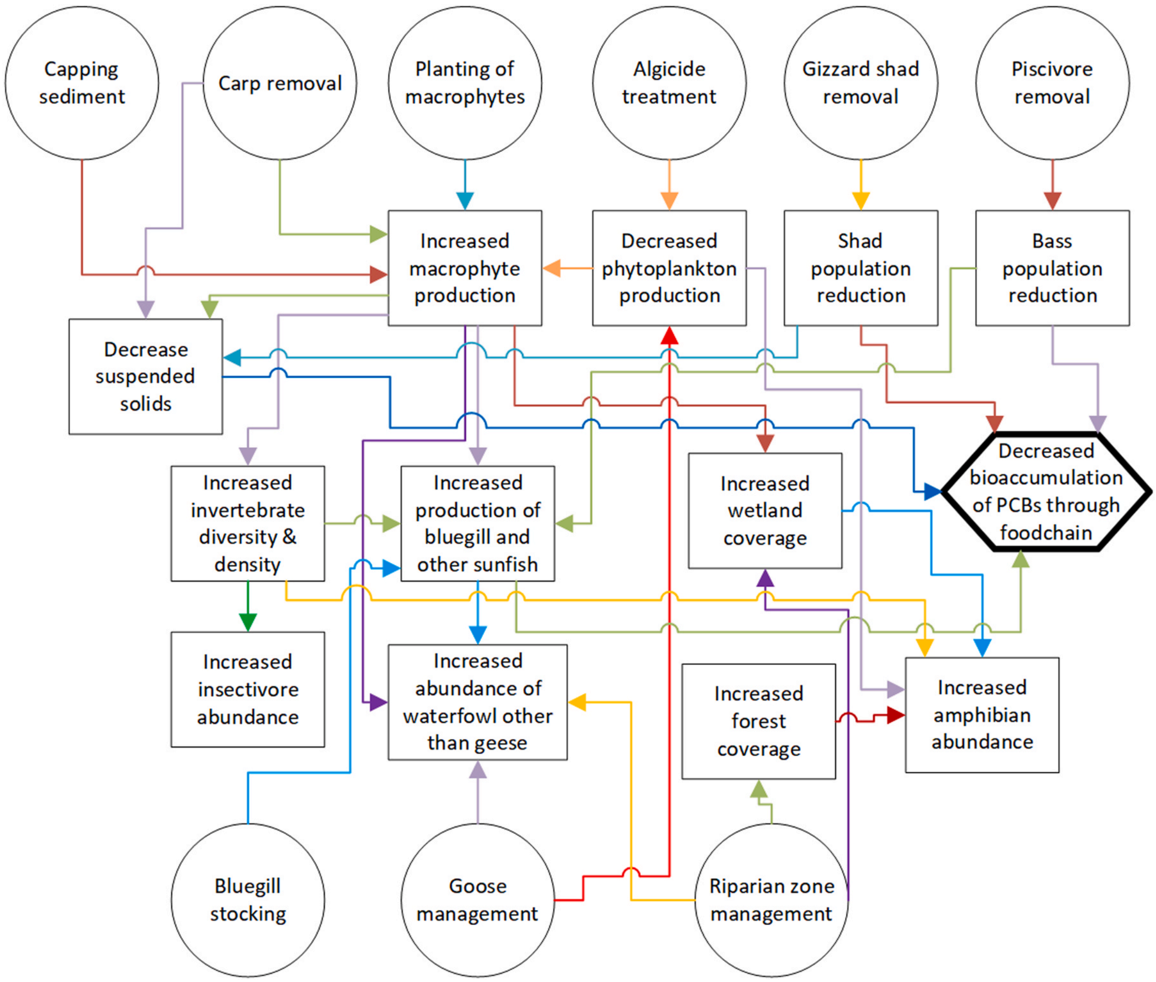

Fig. 2. A conceptual model depicting structural and process changes to the K-1007-P1 Pond under biomanipulation. Circles represent management actions, rectangles are states, and the hexagon is the objective. Lines are colored to allow readers to follow pathways, but differences in colors are not functionally significant. This plan has been followed in ongoing fish management actions for maintenance. Riparian zone management includes planting trees and grading banks.

Table 2
Objectives and activities in the biomanipulation action for the K-1007-P1 Pond at the East Tennessee Technology Park, USA, that affect PCB-induced risk and habitat value.

Risk reduction objective	Remedial activity
Alter fish community to favor fish that do not resuspend, bioaccumulate, or biomagnify PCBs	• Dewater pond. • Remove all fish using rotenone. • Restock pond with desirable fish species, primarily sunfish and minnows. • Modify weir and construct fish barrier between pond and Poplar Creek.
Cover and stabilize contaminated sediments	• Dewater pond. • Recontour portions of pond to create zones of shallow depth. • Plant emergent, floating leaf, and submersed species of aquatic plants (50,000 emergent, 10,000 floating leaf, 5000 submersed plants).
Stabilize shoreline soils and enhance riparian habitat	• Remove invasive plants. • Plant riparian buffer zone, including shrubs and switchgrass, and use prescribed burns to maintain and improve early successional habitat. • Discourage use of pond by Canada geese.

previously as reference areas; (3) the Ridge and Valley physiographic province or ecoregion of the United States; or (4) the Southern Appalachian region that is the focus of the SAMAB [45]. The SAMAB assessment area includes the Northern Piedmont, Southeastern Plains, Blue Ridge, Ridge and Valley, Southwestern Appalachians (including Cumberland Plateau), Central Appalachians, and Interior Plateau [44].

Specific criteria for scoring the habitat value of a pond (supplemental information, Table SI.2) were developed from the broad metrics in Table SI.1 and in [18]. Metrics of habitat value and their regional contexts were selected based on available data. Data related to regional fish abundance are more prevalent than data on benthic invertebrate abundance and much more prevalent than analogous information for plants.

DO concentration was a habitat value metric that was selected as a direct indicator of an aquatic resource's ability to support aquatic life [18]. The habitat value metric for DO assumes a 30-day mean (Table SI.2, [56]) but monitoring was only performed on a few dates in the summer, usually on one date each in June, July, and August.

Biological monitoring efforts at the K-1007-P1 Pond included fish and bird abundance and diversity, and presence of anurans and turtles.

Because the site was relatively devoid of vegetation structure prior to the 2009 biomanipulation, terrestrial wildlife surveys were not a priority. However, to determine long-term colonization and use of the site by wildlife after the establishment of useable habitat, wildlife surveys were conducted with varying frequency following the biomanipulation. These data also helped to confirm the potential value of habitat in the post-biomanipulation state. Terrestrial bird populations were surveyed routinely in developing riparian zones along the pond perimeter to determine any changes in species diversity and density, beginning in the winter of 2009–2010, and annually thereafter. Observations of other wildlife were also recorded during these surveys, either by direct observation or by acoustic surveys. Evening surveys were undertaken separately to record anuran (frog and toad) calls from 2009 to 2021, and hoop nets were set to determine aquatic turtle presence from 2009 to 2021.

3.3. Statistical analyses

All water quality data, annual estimates of percent vegetation coverage, and measurements of PCB concentrations in water were analyzed in a Principal Components Analysis (PCA) to examine relationships among these parameters and how the physicochemical and biological properties of the K-1007-P1 Pond varied annually after remediation. Mean annual values for each water quality parameter (i.e., averaged across transects and across sampling months), including PCB concentrations, were used in the PCA.

The DO vertical-profile data were used to estimate the percentage of the pond's volume with DO < 3 mg/L. This DO threshold was used, as it is slightly lower than the 'low habitat value' quantity in Table SI.2 and has been utilized to describe habitat suitability for fisheries based on dissolved oxygen (i.e., [21,22,28]). The pond bathymetry was estimated from surface area, maximum depth, and mean depth using the package "rLakeAnalyzer," [61] in R version 4.2.1 [40] and based on [42]. The depth at which DO was at the < 3 mg/L threshold was estimated across all transect vertical profiles and averaged, and then paired with the bathymetry to determine the volume of water that was below this threshold. Associations between the maximum proportion of the pond's volume < 3 mg/L and the abundances of fish groups (i.e., natives, sunfish, and nuisance species) were statistically tested using Pearson's product moment correlation coefficients.

Pearson's linear regression fittings were conducted between time (Year) and total PCB concentrations in fish (bluegill and largemouth bass) to explore the temporal trends. Annual attenuation of total PCB concentrations in fish was estimated by the slope of linear regression between the time (Year) and log-transformed PCB concentrations.

4. Results

4.1. PCB concentrations

Mean aqueous PCB concentrations in the K-1007-P1 Pond have fluctuated significantly in the past decade, but concentrations after 2009 remediation activities have generally been lower than concentrations prior to remediation (e.g., 27 ng/L in 2021 compared to 161 ng/L in 2007; Fig. 3). Although decreases in PCBs are significant (Linear regression; slope = −9.2 ng/L/y, R^2 = 0.64, P = 0.0004, Fig. 3), the concentrations measured in the pond are still above concentrations seen at reference sites (<0.3 ng/L) and above the Tennessee water quality criterion for the protection of fish and wildlife (14 ng/L) [52]. Total suspended solids (TSS) have also fluctuated over the past decade but have significantly decreased since remediation took place in 2009 (Linear regression; slope = −0.8 mg/L/y, R^2 = 0.52, P = 0.002, Fig. 3). Fluctuations in PCBs, TSS, and other water quality parameters since remediation may be due to the presence of aquatic vegetation and temporal variation in coverage of that vegetation over time (Fig. 3). Principal Components Analysis illustrated strong correlations among vegetation cover and water clarity (i.e., Secchi depth), PCB concentration, TSS, turbidity, and chlorophyll *a*, and, to a lesser degree, DO and pH (Fig. SI.2). Specifically, when vegetation coverage was high, PCB concentration was low (R = −0.91, P < 0.0001, Fig. SI.3), and TSS, turbidity, chlorophyll *a*, DO, and pH were also low. It is possible that higher vegetation coverage led to greater sediment stability and thus lower resuspension of sediments into the water column. In turn, these lower TSS concentrations were correlated with lower aqueous PCB concentrations as PCBs are hydrophobic contaminants and tend to be particle-associated. The fluctuations in aqueous PCBs over time could also be due to fluctuations in aqueous PCB inputs from storm drains leading to the K-1007-P1 Pond.

PCB concentrations in fish in the K-1007-P1 Pond decreased considerably from 2007 to 2021. Concentrations in bluegill showed a 75% decrease in whole body composites and an 85% decrease in fillet samples during this time period, dropping below both fillet and whole-body tissue concentration targets in 2021 (Fig. 4). Significant negative relationships between years (2007–2021) and total PCB concentrations were observed in both bluegill whole-body (Linear regression; slope = −0.56 µg/g/y, R^2 = 0.52, P < 0.001) (Fig. 4a) and fillet tissues (slope = −0.15 µg/g/y, R^2 = 0.24, P < 0.001) (Fig. 4b). Mean total PCB concentrations in whole body bluegill decreased from 12.05 ± 0.81 µg/g in 2009 (just prior to remediation) to 1.58 ± 0.31 µg/g in 2021, lower than the remedial target (2.3 µg/g) (Fig. 4a). Meanwhile, the concentrations in bluegill fillets decreased from 3.22 µg/g in 2009 to 0.66 ± 0.08 µg/g in 2021. Similar to the concentrations seen in whole-body fish, the concentrations in bluegill fillets oscillated around the 1 µg/g fillet target from 2016 to 2020 and were below this target in 2021 (Fig. 4b).

Total PCB concentrations in largemouth bass fillets have also decreased in the 10 years since remedial actions took place. Across the entire measurement period (2007–2020), there was a significant decreasing trend in total PCB concentrations in largemouth bass fillets

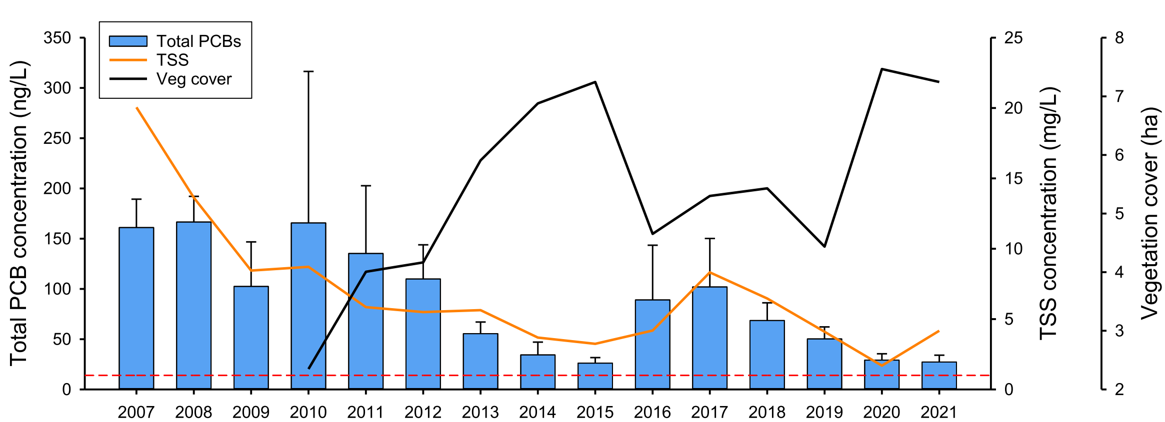

Fig. 3. Means (± standard deviation) for total PCB (ng/L), TSS (mg/L) concentrations in water, and vegetation cover (hectares) in the K-1007-P1 Pond, 2007–2021. Means for PCBs and TSS are based on results across all collections made each year. Dotted line shows the chronic ambient water quality criterion for aqueous PCBs for the protection of fish and aquatic life (14 ng/L).

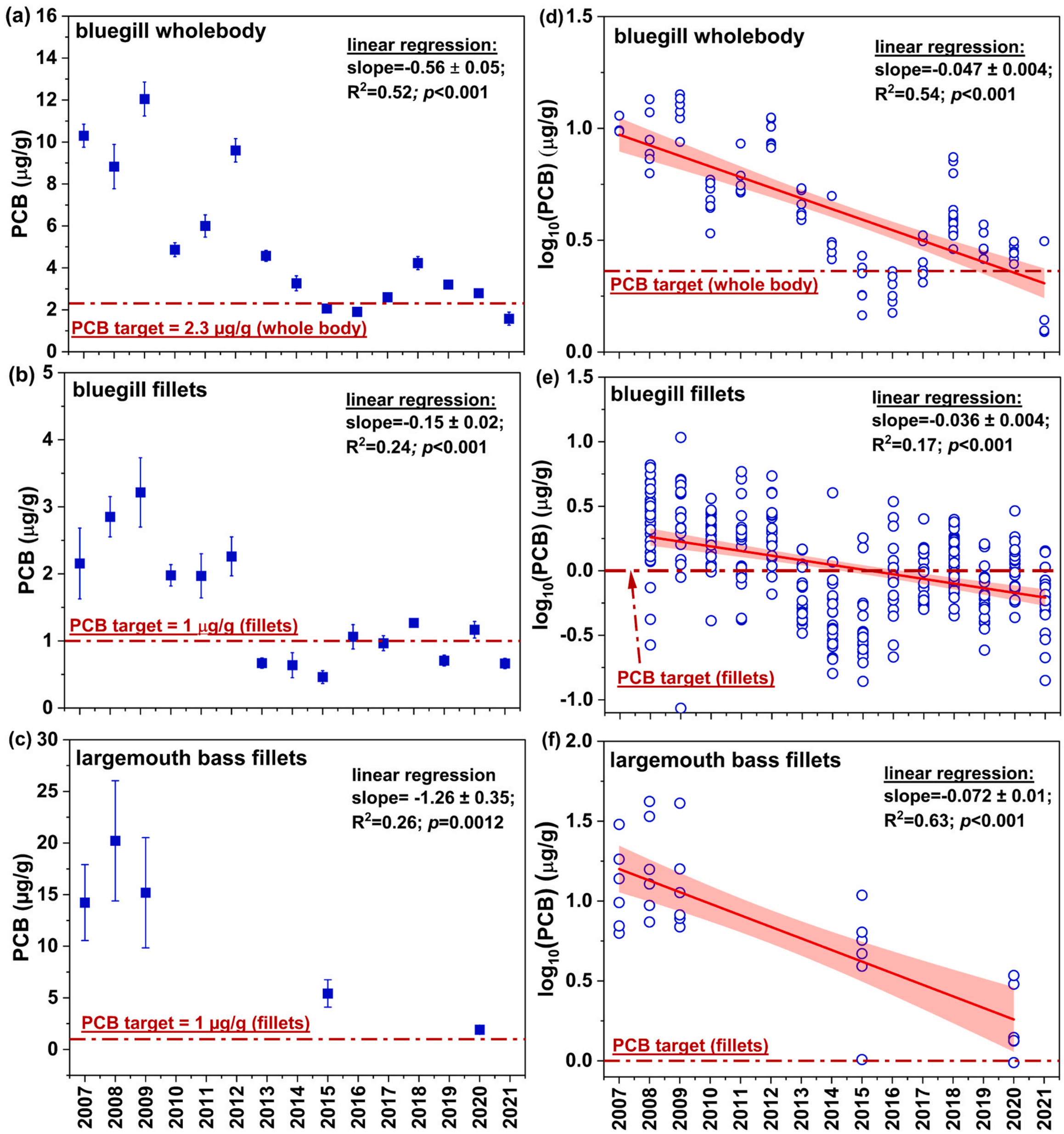

Fig. 4. Mean (± standard error) concentrations of PCBs in (a) whole-body bluegill, (b) bluegill fillets, and (c) largemouth bass fillets from K-1007-P1 Pond, 2007–2021. Linear regressions between $\log_{10}$(PCB) vs. Year and slope estimates are shown in (d)-(f). PCB concentrations represent the sum of Aroclors 1248, 1254, and 1260. The red dashed line in each Figure represents for the target remedial goal in fish, with 2.3 μg/g for whole-body fish and 1 μg/g for fillets. Linear regressions between time (Years) and total PCB concentrations were conducted for each species, and the regression coefficients and p-values are shown in the Figures.

(Linear regression; slope = −1.26 μg/g/y, R^2 = 0.29, P = 0.0012) (Fig. 4c). Concentrations in largemouth bass fillets decreased from 14 to 20 μg/g prior to remediation activities to 1.91 ± 0.42 μg/g in 2020 (Fig. 4c). PCB attenuation rates, estimated using the log-linear regression fitting models (Fig. 4d-f), were 4.7% in bluegill whole body, 3.6% in bluegill fillets, and 7.2% in bass fillets, as estimated by the slope. Although fillet tissue PCB concentrations seen in 2020 were slightly above the 1 μg/g target in this pond, they represent a ten-fold decrease in tissue concentrations compared to pre-biomanipulation concentrations. If this trend continues, concentrations in largemouth bass may be below fillet targets in this pond by the next five-year sampling point (in 2025).

Although biomanipulation activities were intended to decrease PCB exposure to fish, ongoing inputs of PCBs from storm drains leading to the K-1007-P1 Pond could impact effectiveness of remediation. An Engineering Evaluation/Cost Analysis for the remediation predicted that biomanipulation could lead to a 91% reduction in PCB concentrations in largemouth bass if PCB inputs from these storm drains average 232 ng/L [5]. The mean measured PCB concentration in 2020 in SD 100, which leads to the K-1007-P1 Pond, was 53 ng/L. (The wide range of PCB concentrations in SD100 measured quarterly is shown in Table SI.3). The mean PCB concentrations in largemouth bass decreased about 89% between 2007 and 2020.

4.2. Habitat value

Nineteen habitat value metrics were scored (Table 3). Scores for the metrics prior to the biomanipulation of the K-1007-P1 Pond are presented in Table 3 and were reported in [18], a case study of several contaminated sites (including the K-1007-P1 Pond) that illustrated the habitat valuation approach for evaluating remedial actions. Regarding the qualitative scores, 14 of 19 metrics were equivalent before and after

Table 3
Habitat valuation results for K-1007-P1 pond prior to and following biomanipulation.

Metric	2004 Score	2004 Explanation	2010–2021 Score	2010–2021 Explanation
Use value				
Taxa richness—fish	Medium	14 species.	Medium	9–14 species following fish removal action.
Taxa richness—Lepomid sunfish species	High	4 species observed, indicating high-quality littoral zone.	High	4 species observed, indicating high-quality littoral zone.
Taxa richness—waterbirds[2]	High	12 of 15 waterbird species observed in ETTP surveys were at pond.	High	14–24 waterbird species were observed annually, for a total of 27 species.
Number of sensitive fish species	Medium	One sensitive species, spotted sucker.	Medium	One sensitive species, spotted sucker.
Ambient dissolved oxygen concentrations—fish[1]	High	All measurements ≥ 6.4 mg/L in 2004 (range: 6.4–10.3 mg/L; n = 27).	Low to high	High—2010, 2011. 2017, 2020, 2021 had mean values > 5.5 mg/L but minimum measured value was < 3.0 mg/L; Medium—2012, 2013, 2016, 2018; Low—2014, 2015.
Ambient dissolved oxygen concentrations—benthic invertebrates	High	All measurements ≥ 6.4 mg/L in 2004 (range: 6.4–10.3 mg/L; n = 27).	See explanation	High—2010, 2011, 2017, 2020, 2021; Medium—2012, 2013, 2018; Low—2014, 2015, 2016.
Presence of shallow areas for amphibian reproduction	Low to Medium	Pond has only a few floodplain pools at north and southwest end of pond that cannot be accessed by fish.	Medium	Increased aquatic vegetation provides refuge for aquatic amphibians and creates additional semi-isolated pools to support reproduction by aquatic and semi-aquatic taxa.
Number of nonnative or invasive species—fish	Low	One non-North American species, common carp, observed.[2]	Low	One non-North American species, common carp, observed, but in lower densities.
Complexity of habitat structure	High	Pond has woody debris, root wads, undercut banks, boulders, gravel, emergent vegetation, overhanging vegetation, shallows (<0.3 m depth), and deep areas (>3 m depth), but not cobble, sand, or aquatic vegetation. Score is 9 of 12 characteristics.	High	Pond has woody debris, root wads, undercut banks, boulders, gravel, emergent vegetation, aquatic vegetation, overhanging vegetation, shallows (<0.3 m depth), and deep areas (>3 m depth), but not cobble or sand. Score is 10 of 12 characteristics.
Rarity				
Abundance of rare species—fish	Low	No rare fish species present.	Low	No rare fish species present.
Presence of valued community—wetlands	Medium	Forested wetland seep located at southwest side of pond. Floodplain pools also found along north end of pond.	Medium	Wetlands maintained during biomanipulation.
Offsite value added				
Presence of movement corridor—fish	Medium	Pond accessible by upstream fish and rarely by downstream fish during extremely high flows.	Medium	Pond accessible by upstream fish and rarely by downstream fish during extremely high flows.
Presence of movement corridor—avian piscivores	High	ETTP site has largest abundance and diversity of avian piscivores on the ORR and highest density of water bodies, including Mitchell Branch, K-901 pond, K-1007-P1 pond, Poplar Creek, and Clinch River. Heron rookery located on Poplar Creek.	High	ETTP site has largest abundance and diversity of avian piscivores on the ORR and highest density of water bodies, including Mitchell Branch, K-901 pond, K-1007-P1 pond, Poplar Creek, and Clinch River. Heron rookery located on Poplar Creek.
Area of water coverage relative to Southern Appalachian regional average	High	Over 2% of ETTP site (if the Clinch River is included) is covered by water bodies.	High	Over 2% of ETTP site (if the Clinch River is included) is covered by water bodies.
Riparian wetland coverage, relative to Southern Appalachian regional average	High	Riparian wetland coverage much greater than 2%.	High	Riparian wetland coverage much greater than 2%.
Forested riparian coverage, relative to Southern Appalachian regional coverage	Low	Less than 60% of pond riparian zone forested.	Low	Forested riparian area has not changed since before the biomanipulation.
Forested riparian coverage, relative to Ridge and Valley regional coverage	Low	Less than 30% of pond riparian zone forested.	Low	Forested riparian area has not changed since before the biomanipulation.
Adjacent amphibian habitat	Low to Medium	With exception of small areas to southwest and north, combination of mowing and roads surrounding wetlands and pond provides very little buffer area for amphibians.	Medium	Increased vegetation, both aquatic and terrestrial, provides additional usable habitat and refuge for amphibians adjacent to pond. Site remains isolated by roads.
Adjacent reptile habitat	Low to Medium	With exception of small areas to southwest and north, combination of mowing and roads surrounding wetlands and pond provides very little buffer area for reptiles, and mowing introduces high risk of direct mortality and nest disturbance for both terrestrial and aquatic reptiles.	Medium	Increased vegetation, both aquatic and terrestrial, provides additional usable habitat and refuge for reptiles adjacent to pond. Absence of mowing removes potential for direct mortality and nest disturbance. Site remains isolated by roads.

ETTP = East Tennessee Technology Park
[1] 30-day mean, which is the basis for scoring, not measured. Rather, DO assessment was based on the mean DO concentration calculated for each summer. DO was measured at 10-cm depth in each of 3 months (June, July, August) at 3 transects and 3 locations per transect; n = 27 DO measurements per summer. The minimum DO value reflects the minimum DO across the 27 measurements per summer.
[2] Common carp and grass carp collected in 2005.

the biomanipulation. The quality of adjacent amphibian habitat and adjacent reptile habitat was higher following the biomanipulation, and taxa richness of waterbirds remained high but increased in number. Ambient dissolved oxygen was lower in specific locations and times than before the biomanipulation (Table 3).

4.2.1. *Fish community*

Based on relative abundance values, biomanipulation of the pond transitioned it from a nuisance-fish-dominated system to a sunfish-dominated system (Fig. 5A). Prior to the biomanipulation, nuisance fish and sunfish represented 72% and 27% of fish abundance, respectively. Consistent with population goals for remediation, this

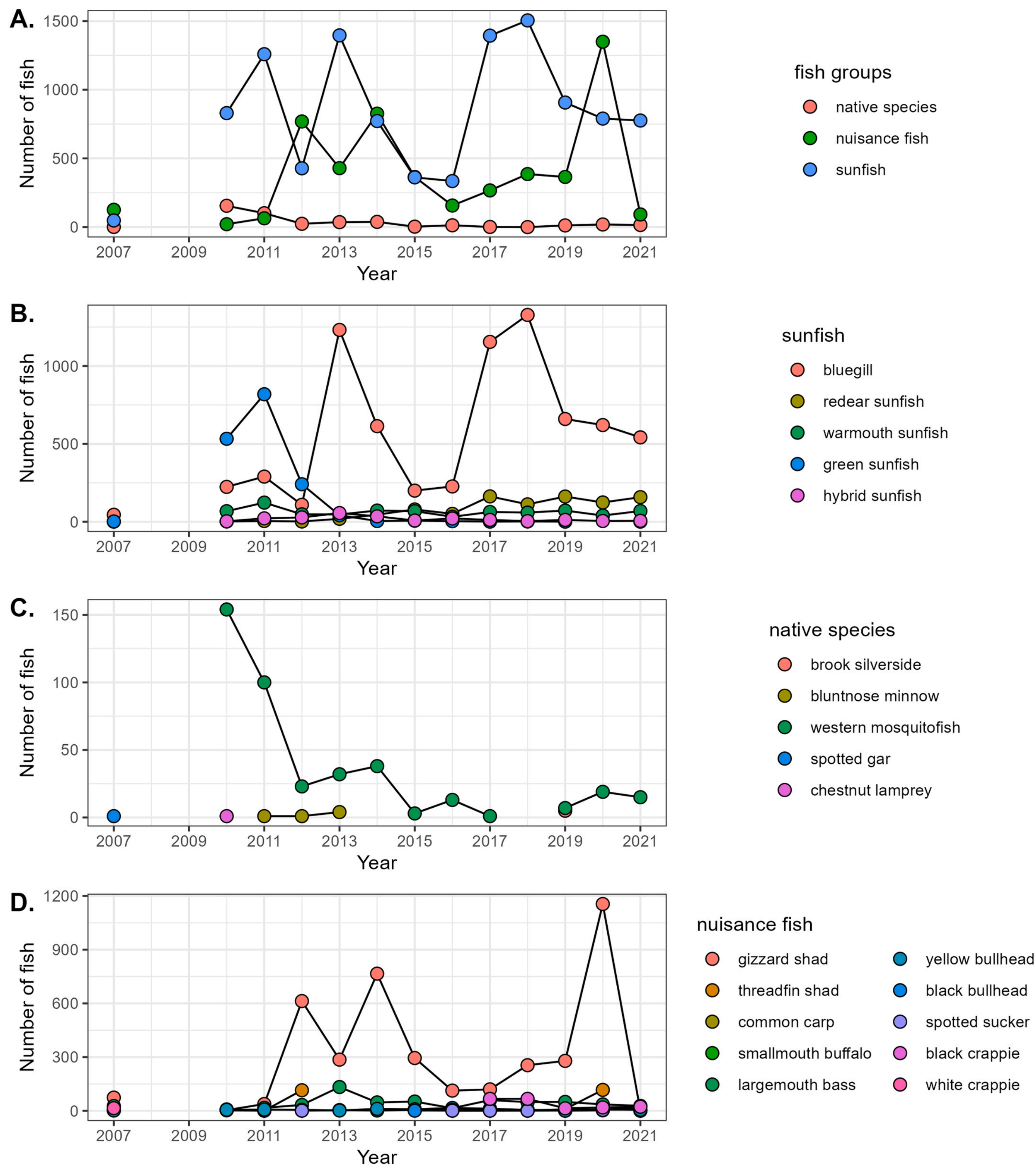

Fig. 5. Comparison of K-1007-P1 Pond fish community abundances (number of fish) from 2007 to 2021. Panels show temporal patterns (A) between fish groups (sunfish versus natives versus nuisance species), (B) within sunfish species only, (C) within native species only, and (D) within nuisance fish species only.

relationship has reversed, with sunfish in 2021 comprising 88% of fish abundance while nuisance species represented 10%. Native species (not including sunfish) have consistently comprised a small proportion of fish abundance, never accounting for more than 16% before or after biomanipulation (Fig. 5A). Nuisance species such as common carp, grass carp, and smallmouth buffalo contributed a substantial amount of the pond's biomass prior to biomanipulation efforts.

The sunfish assemblage has been dominated by bluegill since 2013, but also included redear sunfish (*Lepomis microlophus*), warmouth (*Lepomis gulosus*), and green sunfish (*Lepomis cyanellus*) (Fig. 5B). The western mosquitofish (*Gambusi affinis*) is the most common native species found, while the bluntnose minnow (*Pimephales notatus*) has occurred less frequently (Fig. 5C). Undesirable nuisance species, predominantly gizzard shad, but also including largemouth bass (*Micropterus salmoides*), black crappie (*Pomoxis nigromaculatus*), common carp (*Cyprinus carpio*), small mouth buffalo (*Ictiobus bubalus*), spotted sucker (*Minytrema melanops*), and threadfin shad (*Dorosoma petenense*), among others, remain in the pond at smaller numbers than before the biomanipulation (Fig. 5D).

One of the major habitat value metrics is fish taxonomic richness. Richness has been slow to increase in the pond since the remediation efforts, largely because of a lack of immigration opportunity, which was by design. However, new species have been observed in the pond in recent years. Some of these are desirable species, including minnow species such as brook silverside (*Labidesthes sicculus*) (Table 3). Although richness has been lower until recently, the Lepomid sunfish richness remains high with four species observed regularly, indicative of high habitat value (Table 3).

Based on DO measured at 10-cm depth (Table 3), DO was at its lowest level in 2014 (mean = 1.4 mg/L) and 2015 (2.09 mg/L), and considerably lower than the concentrations measured from 2004 to 2013 (mean values ranged from 4.7 mg/L in 2013 to 8.6 mg/L in 2004). DO increased after 2014, reaching levels of 6.5 and 5.7 mg/L in 2020 and 2021, respectively. In most years, these DO levels indicate potential slight to moderate impairment of production of warmwater fish [56], and levels in 2014 and 2015 indicate potential severe impairment of production of warmwater fish (Table SI.2).

The percentage of the pond with critically low DO, followed a similar temporal pattern to mean DO concentrations at 10-cm depth, with over 90% of the pond estimated to be < 3 mg/L in summer 2014 and 2015 (Fig. SI.4). The abundance of native fish species was negatively correlated with the maximum percentage of the pond with DO < 3 mg/L for a

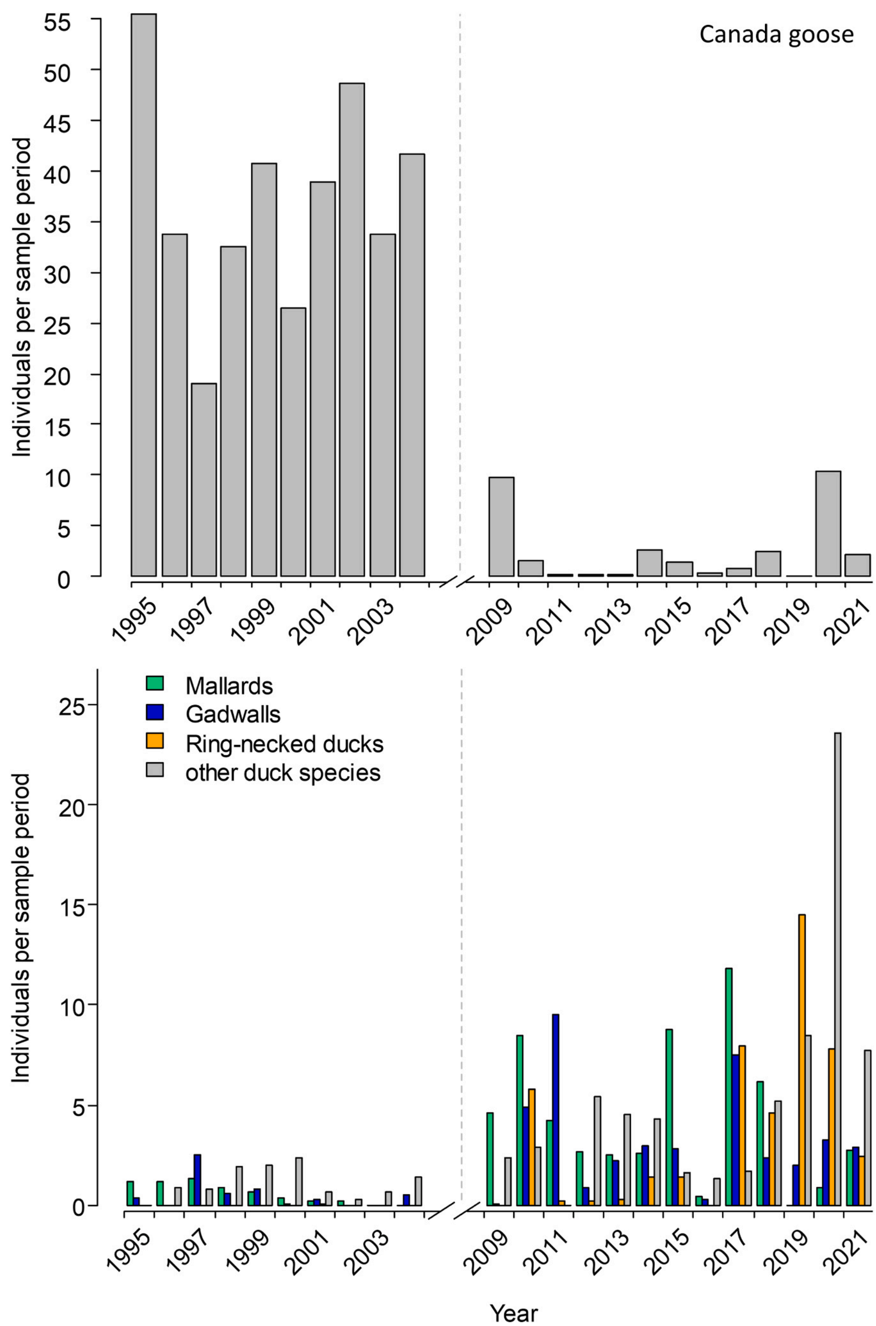

Fig. 6. Mean numbers of Canada geese (top) and ducks (bottom) observed per survey at the pond before (1995–2004) and after (2009–2021) the biomanipulation (indicated by dotted vertical line). Number of surveys each year is reported in (Peterson 2018).

given summer (R=−0.657, P = 0.04), while there was no correlation with nuisance fish abundance (R=0.037, P = 0.92) nor sunfish abundance (R=−0.364, P = 0.30). Because fish and DO data were not collected at the same time, fish data from February surveys were correlated with DO data measured the prior summer.

4.2.2. Bird, reptile, and amphibian populations

Waterbird species that had not been observed before the biomanipulation began to be observed after 2009. The least bittern (*Ixobrychus exilis*) had never been observed anywhere else on the ORR and was not known to occur at the K-1007-P1 Pond before July 2012. New ducks and geese included snow goose (*Chen caerulescens*), blue-winged teal (*Anas discors*), green-winged teal (*Anas crecca*), northern shoveler (*Anas clypeata*), redhead (*Aythya americana*), lesser scaup (*Aythya affinis*), bufflehead (*Bucephela albeola*), ruddy duck (*Oxyura jamaicensis*), and red-breasted merganser (*Mergus serrator*). The mean numbers of observations per survey (by year) for ducks is depicted in Fig. 6, clearly increasing after the biomanipulation. Specific results for four duck species—hooded merganser (*Lophodytes cucullatus*), ring-necked duck (*Aythya collaris*), gadwall (*Anas strepera*), and mallard (*Anas platyrhynchos*)—are shown in Figures in (Peterson 2018). Additional species of note were the common gallinule (*Gallinula galeata*), which is listed in Tennessee as In Need of Management and sora (*Porzana carolina*) and little blue heron (*Egretta caerulea*), which are rare breeders in Tennessee. These species benefited from the abundant aquatic vegetation and marsh-like habitat created during the remedial action.

In addition, the number of wintering bird species recorded in riparian zones around the K-1007-P1 Pond increased between the winters of 2009–2010 ($n = 7$) and 2010–2011 ($n = 14$) and the winters of 2011–2012 ($n = 23$) and 2012–2013 ($n = 28$). The swamp sparrow (*Melospiza georgiana*), a bird of freshwater marshes and swamps, was notably absent in the winter of 2009–2010 but has been present every winter since then. Ten sparrow species have been recorded at the K-1007-P1 Pond since 2009, including four just since 2014: vesper sparrow (*Pooecetes gramineus*), fox sparrow (*Passerella iliaca*), American tree sparrow (*Spizella arborea*), and Lincoln's sparrow (*Melospiza lincolnii*).

Organized survey data for amphibians and reptiles were not available pre-biomanipulation. However, limited observation indicated the presence of bullfrogs (*Lithobates catesbeianus*) and green frogs (*L. clamitans*) in the pond. In the year following biomanipulation (2010), eight additional anuran taxa were detected at least once (Table 4), including the first observations of eastern narrow-mouthed toad (*Gastrophryne carolinensis*), Cope's gray treefrog (*Hyla chrysoscelis*), spring peeper (*Pseudacris crucifer*), and northern cricket frog (*Acris crepitans*). In 2011, two medium-sized semi-aquatic species, the southern leopard frog (*Lithobates sphenocephalus*) and pickerel frog (*Lithobates palustris*), were observed. These species are typical of densely vegetated wetlands and streams. The terrestrial, ephemeral wetland-breeding species, upland

Table 4
Species of turtles and frogs detected at the K-1007-P1 Pond, 2009–2021. Shaded cells represent presence based on incidental observation, and dots represent confirmed detection during targeted surveys.

Species	09	10	11	12	13	14	15	16	17	18	19	20	21
Turtles													
Cumberland slider		•	•	•	•	•	•	•	•	•	•	•	•
Eastern spiny softshell turtle		•	•	•	•	•	•	•	•	•	•	•	•
Common snapping turtle			•	•	•	•	•	•	•	•	•	•	•
Eastern musk turtle			•	•	•	•	•	•	•	•	•	•	•
Midland painted turtle						•			•	•		•	•
Pond slider												•	•
River Cooter													•
Anurans													
American bullfrog	•	•	•	•	•	•	•	•	•	•		•	•
Green frog	•	•	•	•	•	•	•	•	•	•	•	•	•
Cope's gray treefrog		•	•	•	•	•	•	•	•	•	•	•	•
Spring peeper		•	•	•	•	•	•	•	•	•	•	•	•
Eastern narrow-mouthed toad*		•	•		•		•	•	•	•		•	•
Northern cricket frog		•	•	•			•	•				•	•
Southern leopard frog			•	•	•	•	•	•	•	•		•	•
Pickerel frog			•	•	•	•	•	•		•		•	•
Upland chorus frog					•			•	•	•		•	•
American toad					•				•	•		•	

* Observed breeding in rain-filled pools adjacent to P1 Pond.

chorus frog (*Pseudacris feriarum*) and American toad (*Anaxyrus americanus*), were not observed until 2013. The highly vagile turtle species, Cumberland slider (*Trachemys scripta troostii*) and eastern spiny softshell (*Apalone spinifera*), were first observed in 2010. This observation was followed by common snapping turtles (*Chelydra serpentina*) and musk turtles (*Sternotherus odoratus*) in 2011. Midland painted turtles were first observed in 2014, and pond sliders (*Trachemys scripta*) and the more fluvial species, river cooter (*Pseudemys concinna*), were first observed in 2020 and 2021, respectively (Table 4).

5. Discussion

In 2009, biomanipulation of the fish and plant communities at a PCB-contaminated pond in East Tennessee, USA, was carried out to reduce human health and ecological risk. We evaluated the success of the remedial action by assessing habitat value and PCB concentrations in fish. Risk reduction objectives included altering the fish community to reduce sediment suspension, biomagnification, and bioaccumulation, covering and stabilizing contaminated sediments, and stabilizing shoreline soils and enhancing riparian habitat. A few categories of habitat value metrics (amphibian and reptile habitat, taxa richness of waterbirds) and PCB concentrations in fish improved since the biomanipulation. In the most recent sampling year (2021), PCB concentrations in bluegill were below the risk-based target level while PCB concentrations in largemouth bass (in 2020) were above the target level.

Conventional remediation of PCB-contaminated sites typically involves removal or capping of sediment or filling in a pond, often creating a parking lot, all of which can have significant environmental and financial costs. Removal of sediment and filling in the pond were evaluated as alternative remedial actions to the biomanipulation [5], but biomanipulation was anticipated to be the least expensive and most cost-effective remedial alternative. Excavation would have eliminated habitat for many ecological populations and subpopulations while reducing PCB sources. Clearly, without a pond, habitat and habitat value for fish, waterbirds, and amphibians, and presence of wetlands and forested riparian coverage would be nonexistent or much lower, depending on the scale of analysis. Furthermore, excavation would have decreased ecological connectivity, which is an important consideration as remedial options are evaluated [7]. Moreover, because policies may drive the decision to remediate sediments before the sources of contaminants to the system are completely controlled, the decision needs to reflect potential for re-contamination of remediated systems. Cost estimates for remediation of this pond (based on present value in 2006), including capital costs and operations and maintenance, were $27.1 million for the sediment removal alternative, and $9.9 million for the filled-in pond alternative, which would have removed the ecosystem entirely. The biomanipulation alternative, estimated at $4.1 million, represented a significant cost savings compared to these two alternatives [5].

Biomanipulation has been recommended by others to reduce ecological or human exposure to chemical contaminants. For example, Stow et al. [51] suggested that replacing lake trout with less-contaminated rainbow trout could reduce human exposure to PCBs. Lepak et al. (2012) [32] stocked low-mercury prey to reduce mercury concentrations in Northern pike through a "growth dilution" experiment in a lake in Colorado, USA. Based on their short-term success, they asserted that "perhaps the most effective method of perpetually reducing sport fish Hg concentrations" would be to manage for a naturally reproducing forage fish population.

The changes in the fish community at the K-1007-P1 Pond were associated with a reduction in PCBs in water and fish, but natural attenuation of the chemicals was likely a contributing factor that will continue to operate. Since the 1977 ban on PCB manufacture and use in the United States, studies have shown long-term declines in PCB concentrations in fish, even in the absence of targeted remediation. For example, in the Great Lakes, investigators have found a rapid decline (between 16.7% and 23.9% per year) in PCB concentrations in fish in the years immediately following the ban and a more gradual decline (2.6–4.0% per year) in the years subsequent to that [41]. Natural attenuation of PCBs in minnows and sunfish in tributaries on the ORR have ranged from 0% to 8% per year and in catfish in a large reservoir system adjacent to the ORR have ranged from 5.4% to 11.3% per year [33]. While the natural attenuation of the PCBs in bluegill and largemouth bass at impounded stream sites on the ORR over the past 30 years was not significant [33], in the present study we have observed significant and rapid declines in PCB concentration in these two fish species in the pond since remediation actions were taken, ranging from 3.6% to 7.2% per year. The declines of PCBs in these pond fish indicate the remedial practices largely enhanced the mitigation of PCB bioaccumulation in the pond.

As planned, the pond's water column was transformed from pelagic to vegetated, reducing light levels that would have otherwise supported phytoplankton production (a food resource for planktotrophic species) and now providing higher dimensional habitat for fish and invertebrates. The creation of vast shallow areas and the introduction of these plants created much-needed refuge for many species of fish and potentially limited gizzard shad densities. Bluegill use aquatic vegetation as refuges, though there can be a tradeoff between safety from predators and foraging success among juveniles [24]. This change in water column habitat, combined with the removal of PCB-bioaccumulating species, enabled sunfish to become the numerically dominant taxonomic group within the pond's fish assemblage. Whereas bluegill are the numeric dominants (~70% of all sunfish in 2021), the relatively stable populations of the other three sunfish species, particularly the redear and warmouth, indicate populations with successful reproduction and recruitment. Further, while sunfish populations appeared to be increasing or stable, populations of undesirable species, particularly gizzard shad and largemouth bass, continue to remain low and do not appear to impede bluegill reproduction and recruitment, though there is evidence that both species are reproducing in the pond. Other undesirable species such as common carp and smallmouth buffalo do not appear to be reproducing in the pond, based on a lack of juvenile-sized cohorts.

A potential concern with respect to fish habitat quality is the low measured DO concentrations, especially in 2014 and 2015. This low DO occurred when vegetation coverage was high, a pattern observed in other aquatic ecosystems [31,43,55]. Potential mechanisms for low DO in highly vegetated areas include reduced air-water gas exchange, decreased light availability for photosynthesis, greater root respiration, and increased microbial respiration fueled by senescent aquatic vegetation [31]. Because of these low-DO conditions, lower sunfish abundances have been observed in areas of dense aquatic vegetation [36], and a similar relationship was observed for native fish species in the K-1007-P1 Pond. Avoidance behavior or acclimation under hypoxic conditions is common [11], with many sunfish showing avoidance behavior [31]. In any case, whereas fish richness is high, and some fish are known to be reproducing, some negative impacts on fish populations (e.g., growth, reproduction, mortality) due to low DO are possible.

DO was generally lower in years with greater aquatic vegetation coverage, suggesting a potential tradeoff between greater vegetation coverage stabilizing sediments and reducing PCB concentrations in water and fish, versus lowering DO concentrations critical for fish survival. However, in the two most recent years of measurement, vegetation coverage was at its highest while DO concentrations fell under the 'high' habitat value category (Table SI.2), possibly due to variation in the density or patchiness of vegetation, although these metrics were not quantified. It is important to note that the DO measurements reported here were taken once in June, July, and August at specific transect locations, and may not be representative of conditions experienced by fish each summer. The lack of time-series data makes any conclusions about impairments uncertain [11], especially as DO concentrations are known to vary at hourly, daily, and seasonal time scales, with even greater variation within vegetation patches [23]. Continued monitoring of DO is important, and more-frequent monitoring would increase certainty whereas more spatially distributed measurements could better resolve potential variation due to vegetation patchiness.

Changes in amphibian abundance were expected as a result of enhanced water quality and lowered PCB concentration [4]. However, the increase in vegetation and habitat structure probably played a larger role in shaping both amphibian and reptile communities. The transition from open water to more structured emergent vegetation communities represents an increase in habitat value in terms of relative rarity and structural habitat complexity. Specifically, a shift in amphibian community composition from perennial and generalist taxa such as bullfrogs (*Lithobates catesbeianus*) and green frogs (*L. clamitans*) to more seasonal and specialist taxa such as *Pseudacris* spp and American toads (*Anaxyrus americanus*) would be expected, because vegetation and recontouring provided enhanced opportunities for reproduction (i.e., availability of semi-isolated pools) and reduced potential for competition, predation, and general exposure [2,39]. These patterns are somewhat apparent in the years following biomanipulation. Unfortunately, organized anuran survey data were not available for the pre-biomanipulation period. Nonetheless, bullfrogs and green frogs, at least, were present before biomanipulation, whereas most seasonal taxa were generally considered absent, owing to a paucity of suitable breeding habitat.

Changes in the terrestrial vegetation community increased the availability of upland refuge and cover for rarer seasonal breeders, which are more sensitive to habitat fragmentation than generalist taxa such as bull frogs [25]. Although relevant data were lacking for terrestrial reptiles, the increased structural vegetation complexity likewise provides additional useable habitat, while reduced mowing minimizes direct mortality [10,16,46]. The site remains surrounded by roads and thus is semi-isolated.

Increased waterfowl diversity was an expected result of the PCB biomanipulation undertaken at the pond. Specifically, transformation from a typical suburban pond setting to a more natural habitat was expected to result in fewer Canada geese but increased numbers of other waterfowl. The main changes were expected during winter months, when the East Tennessee region supports waterfowl populations, including ducks that migrate from other areas in North America. Canada geese became less abundant. The cessation of mowing and planting of shrubs was consistent with models that predict Canada goose presence and probability of Canada goose presence based on percent pasture surrounding a survey plot [34]. Conditions for ducks improved. The biomanipulation was also beneficial to wintering terrestrial bird populations. Robust riparian zones with diverse structure (shrubs adjacent to switchgrass) provide excellent cover and foraging habitat for these populations. If the riparian zone is permitted to succeed to forest as was discussed in [18], different species may benefit.

Environmental benefits and costs of remediation alternatives can be compared [17], especially when remediation alternatives are potentially destructive to ecosystems [60]. For example, Schwabe et al. [47]; Etnier, Starnes [20]; Peterson et al. [38]; Semlitsch, Bodie [48]; TNC [53] argued for a net benefits approach for estimating non-market values associated with ecosystem services provided by the contaminated Salton Sea, California. Along with measurements of chemical contaminants, habitat value metrics are useful performance metrics for remedial actions [18,47]. Clearly, biomanipulation would have greater net environmental benefits than excavation at many contaminated sites.

6. Conclusions

Biomanipulation is not typically considered as a remediation alternative for chemical contaminants, but over a decade of monitoring has shown it to be effective for risk reduction from PCBs in the K-1007-P1 Pond in East Tennessee, USA. Risk reduction objectives were to alter the fish community to favor fish that do not resuspend, bioaccumulate, or biomagnify PCBs; to stabilize contaminated sediments to improve water quality; and to stabilize shoreline soils and enhance riparian habitat. The first twelve years following biomanipulation of the K-1007-P1 Pond show lower PCB concentrations and mortality and reproductive benefits for the altered fish community. A few categories of habitat value metrics (amphibian and reptile habitat, taxa richness of waterbirds) improved since the biomanipulation. In the most recent sampling year (2021), PCB concentrations in bluegill were below the risk-based target level. In many contaminated environments, biomanipulation may be an effective option for remediation that reduces chemical concentrations in environmental media and wildlife and preserves or enhances ecosystem services, such as species habitat.

CRediT authorship contribution statement

Rebecca A. Efroymson: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization; **Mark J. Peterson:** Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Project administration, Funding acquisition, Visualization; **R. Trent Jett:** Data analysis, Writing - original draft, Writing - review & editing; **Natalie A. Griffiths:** Formal analysis, Writing - original draft, Writing – review & editing, Visualization, Supervision; **Evin T. Carter:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration; **Allison M. Fortner:** Investigation, Data curation, Writing - original draft, Visualization; **Christopher R. DeRolph:** Visualization, Writing - review & editing; **Peijia Ku:** Formal analysis, Investigation, Visualization, Writing – review & editing; **Paul G. Matson :** Formal analysis, Writing - review & editing, Visualization; **Rachel M. Pilla:** Formal analysis, Visualization, Writing - review & editing; **Teresa J. Mathews:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2023.132587.

References

[1] APHA. 2005. Standard methods for the examination of water and wastewater, 21st edition, American Public Health Association, Washington D.C., USA.

[2] Bell, S.S., E.D. McCoy, and H.R. Mushinsky. 1991. Habitat structure: the physical arrangement of objects in space. Chapman and Hall, London, England.

[3] Bevelhimer, M.S., B.E. Sample, G.R. Southworth, J.J. Beauchamp, and M.J. Peterson. 1997. Estimations of whole-fish contaminant concentrations from fish fillet data. Oak Ridge National Laboratory, Oak Ridge, TN.

[4] Birge, W.J., J.A. Black, and A.G. Westerman. 1978. Effects of polychlorinated biphenyl compounds and proposed PCB-replacement products on embryo-larval stages of fish and amphibians. University of Kentucky, Water Resources Research Institute, Lexington, Kentucky.

[5] BJC. 2006. Engineering evaluation/cost analysis for the ponds at the East Tennessee Technological Park. Prepared for U.S. Department of Energy, Environmental Management Program, Oak Ridge, TN, Bechtel-Jacobs Corporation.

[6] BJC. 2010. Removal Action Report for ponds at the East Tennessee Technology Park, Oak Ridge, Tennessee: K-1007-P Holding Ponds, K-901-A Holding Pond, K-720 Slough, and K-770 Embayment. Prepared for U.S. Department of Energy, Environmental Management Program, Oak Ridge, TN, Bechtel-Jacobs Corporation.

[7] Burger, J., 2019. A framework for increasing sustainability and reducing risk to ecological resources through integration of remediation planning and implementation. Environ Res 172, 586–595.

[8] Burger, J., Gochfeld, M., Jeitner, C., 2018. Risk valuation of ecological resources at contaminated deactivation and decommissioning facilities: methodology and a case study at the Department of Energy's Hanford site. Environ Monit Assess 190, 19.

[9] Carpenter, S.R., Kitchell, J.F., Hodgson, J.R., 1985. Cascading trophic interactions and lake productivity. Bioscience 35, 634–639.

[10] Carter, E.T., Ravesi, M.J., Eads, B.C., Kingsbury, B.A., 2017. Invasive plant management creates ecological traps for snakes. Biol Invasions 19, 443–453.

[11] Davis, J.C., 1975. Minimal dissolved-oxygen requirements of aquatic life with emphasis on Canadian species - review. J Fish Res Board Can 32, 2295–2332.

[12] DeVault, D.S., Hesselberg, R., Rodgers, P.W., Feist, T.J., 1996. Contaminant trends in lake trout and walleye from the Laurentian Great Lakes. J Gt Lakes Res 22, 884–895.

[13] Devries, D.R., Stein, R.A., 1992. Complex interactions between fish and zooplankton - quantifying the role of an open-water planktivore. Can J Fish Aquat Sci 49, 1216–1227.

[14] DOE. 2007. Action memorandum for the ponds at the East Tennessee Technology Park, Oak Ridge, Tennessee: K-1007-P Holding Ponds, K-901-A Holding Pond, K-720 Slough, and K-770 Embayment. U.S. Department of Energy, Environmental Management Program, Oak Ridge, TN.

[15] DOE. 2010. Removal action work plan for the removal action at the ponds at the East Tennessee Technology Park, Oak Ridge, Tennessee. U.S. Department of Energy, Environmental Management Program, Oak Ridge, TN.

[16] Durbian, F., Farmer, A., 2006. Estimating shorebird numbers at migration stopover sites. Condor 108, 792–807.

[17] Efroymson, R.A., Nicolette, J.P., Suter, G.W., 2004. A framework for net environmental benefit analysis for remediation or restoration of contaminated sites. Environ Manag 34, 315–331.

[18] Efroymson, R.A., Peterson, M.J., Welsh, C.J., Druckenbrod, D.L., Ryon, M.G., Smith, J.G., Hargrove, W.W., Giffen, N.R., Roy, W.K., Quarles, H.D., 2008. Investigating habitat value to inform contaminant remediation options: approach. J Environ Manag 88, 1436–1451.

[19] Ehsani, S., Hayes, D., 2018. Efficacy of dredging for remediating polychlorinated biphenyl-contaminated sediments of the Lower Fox River. Environ Eng Sci 35, 1387–1393.

[20] Etnier, D.A., and W.C. Starnes. 1993. The Fishes of Tennessee. The University of Tennessee Press, Knoxville, TN.

[21] Fang, X., Stefan, H.G., 2009. Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous United States under past and future climate scenarios. Limnol Oceanogr 54, 2359–2370.

[22] Fang, X., Stefan, H.G., Eaton, J.G., McCormick, J.H., Alam, S.R., 2004. Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios - Part 1. Cool-water fish in the contiguous US. Ecol Model 172, 13–37.

[23] Goodwin, K., Caraco, N., Cole, J., 2008. Temporal dynamics of dissolved oxygen in a floating-leaved macrophyte bed. Freshw Biol 53, 1632–1641.

[24] Gotceitas, V., 1990. Foraging and predator avoidance - a test of a patch choice model with juvenile bluegill sunfish. Oecologia 83, 346–351.

[25] Hager, H.A., 1998. Area-sensitivity of reptiles and amphibians: Are there indicator species for habitat fragmentation? Ecoscience 5, 139–147.

[26] Hairston, N.G., Smith, F.E., Slobodkin, L.B., 1960. Community structure, population control, and competition. Am Nat 94, 421–425.

[27] Interstate Technology and Regulatory Council. 2004. Making the case for ecological enhancements: a white paper.

[28] Jacobson, P.C., Stefan, H.G., Pereira, D.L., 2010. Coldwater fish oxythermal habitat in Minnesota lakes: influence of total phosphorus, July air temperature, and relative depth. Can J Fish Aquat Sci 67, 2002–2013.

[29] Kapustka, L.A., 2003. Rationale for use of wildlife habitat characterization to improve relevance of ecological risk assessments. Hum Ecol Risk Assess 9, 1425–1430.

[30] Kapustka, L.A., Galbraith, H., Luxon, M., Yocum, J., 2001. Using landscape ecology to focus ecological risk assessment and guide risk management decision-making. Toxicol Ind Health 17, 236–246.

[31] Killgore, K.J., Hoover, J.J., 2001. Effects of hypoxia on fish assemblages in a vegetated waterbody. J Aquat Plant Manag 39, 40–44.

[32] Lepak, J.M., Hooten, M.B., Johnson, B.M., 2012. The influence of external subsidies on diet, growth and Hg concentrations of freshwater sport fish: implications for management and fish consumption advisories. Ecotoxicology 21, 1878–1888.

[33] Matson, P.G., Stevenson, L.M., Efroymson, R.A., Jett, R.T., Jones, M.W., Peterson, M.J., Mathews, T.J., 2022. Variation in natural attenuation rates of polychlorinated biphenyls (PCBs) in fish from streams and reservoirs in East Tennessee observed over a 35-year period. J Hazard Mater 438, 14.

[34] McAlister, M.A., DePerno, C.S., Fuller, J.C., Howell, D.L., Moorman, C.E., 2017. A comparison of field methods to estimate Canada Goose abundance. Wildl Soc Bull 41, 685–690.

[35] McDonough, T.A., and G.D. Hickman. 1999. Reservoir fish assemblage index development: a tool for assessing ecological health in Tennessee Valley Authority impoundments, CRC Press, Boca Raton, FL.

[36] Miranda, L.E., Hodges, K.B., 2000. Role of aquatic vegetation coverage on hypoxia and sunfish abundance in bays of a eutrophic reservoir. Hydrobiologia 427, 51–57.

[37] MPCA. 2014. Human health-based water quality standards technical support document. Minnesota Pollution Control Agency, St. Paul, MN.

[38] Peterson, M.J., Mathews, T.J., Jett, R.T., McManamay, R.A., Herold, J.M., Fortner, A.M., Jones, M.W., Darling, S.E., Tobin, E.E. 2018. Operational and performance monitoring of ETTP Ponds – 2018 results. ORNL, Oak Ridge National Laboratory, Oak Ridge, TN.

[39] Purrenhage, J.L., Boone, M.D., 2009. Amphibian community response to variation in habitat structure and competitor density. Herpetologica 65, 14–30.

[40] R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ⟨https://www.R-project.org/⟩.

[41] Rasmussen, P.W., Schrank, C., Williams, M.C.W., 2014. Trends of PCB concentrations in Lake Michigan coho and chinook salmon, 1975-2010. J Gt Lakes Res 40, 748–754.

[42] Read, J.S., Hamilton, D.P., Jones, I.D., Muraoka, K., Winslow, L.A., Kroiss, R., Wu, C.H., Gaiser, E., 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environ Model Softw 26, 1325–1336.

[43] Rose, C., Crumpton, W.G., 1996. Effects of emergent macrophytes on dissolved oxygen dynamics in a prairie pothole wetland. Wetlands 16, 495–502.

[44] SAMAB. 1996. The Southern Appalachian assessment aquatics technical report. Southern Appalachian Man and the Biosphere. www.samab.org.

[45] SAMAB. 2019. Southern Appalachian Assessment. Southern Appalachian Man and the Biosphere. www.samab.org.

[46] Saumure, R.A., Herman, T.B., Titman, R.D., 2007. Effects of haying and agricultural practices on a declining species: The North American wood turtle, Glyptemys insculpta. Biol Conserv 135, 565–575.

[47] Schwabe, K.A., Schuhmann, P.W., Baerenklau, K.A., Nergis, N., 2008. Fundamentals of estimating the net benefits of ecosystem preservation: the case of the Salton Sea. Hydrobiologia 604, 181–195.

[48] Semlitsch, R.D., Bodie, J.R., 2003. Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. Conserv Biol 17, 1219–1228.

[49] Sharma, C., Borgstrøm, R., Rosseland, B., 2010. Chapter 15: Biomanipulation in Lake Årungen, Norwar: a tool for biological control. In: Ansari, A., Gill, S., Lanza, G., Rast, W. (Eds.), Eutrophication: Causes, Consequences and Control. Springer, Dordrecht, pp. 295–324.

[50] Smoot, J.C., Findlay, R.H., 2010. Caloric needs of detritivorous gizzard shad Dorosoma cepedianum are met with sediment bacterial and algal biomass. Aquat Biol 8, 105–114.

[51] Stow, C.A., Carpenter, S.R., Madenjian, C.P., Eby, L.A., Jackson, L.J., 1995. Fisheries management to reduce contaminant consumption. Bioscience 45, 752–758.

[52] TDEC. 2019. Rules of the Tennessee Department of Environment and Conservation. Chapter 0400–40-03. General Water Quality Criteria. TN Department of Environment and Conservation, Nashville, TN.

[53] TNC. 1995. The Oak Ridge Reservation, biodiversity, and the common ground process final report. Prepared by The Nature Conservancy for Barge, Waggoner, Sumner and Cannon, Inc. for the Common Ground Process at the Oak Ridge Reservation managed by Lockheed Martin Energy Systems, Inc. for the U.S. Department of Energy, Oak, Ridge, TN.

[54] Triest, L., Stiers, I., Van Onsem, S., 2016. Biomanipulation as a nature-based solution to reduce cyanobacterial blooms. Aquat Ecol 50, 461–483.

[55] Turner, A.M., Cholak, E.J., Groner, M., 2010. Expanding American Lotus and Dissolved Oxygen Concentrations of a Shallow Lake. Am Midl Nat 164, 1–8.

[56] USEPA. 1986. Ambient water quality criteria for dissolved oxygen. Office of Water, US Environmental Protection Agency, Washington, DC.

[57] USEPA. 2017. Water quality standards handbook-Chapter 3. Office of Water, US Environmental Protection Agency, Washington, DC.

[58] VanMiddlesworth, T.D., McClelland, N.N., Sass, G.G., Casper, A.F., Spier, T.W., Lemke, M.J., 2017. Fish community succession and biomanipulation to control two common aquatic ecosystem stressors during a large-scale floodplain lake restoration. Hydrobiologia 804, 73–88.

[59] Wenger, A.S., Harvey, E., Wilson, S., Rawson, C., Newman, S.J., Clarke, D., Saunders, B.J., Browne, N., Travers, M.J., McIlwain, J.L., Erftemeijer, P.L.A., Hobbs, J.P.A., McLean, D., Depczynski, M., Evans, R.D., 2017. A critical analysis of the direct effects of dredging on fish. Fish Fish 18, 967–985.
[60] Whicker, F.W., Hinton, T.G., MacDonell, M.M., Pinder, J.E., Habegger, L.J., 2004. Environment - avoiding destructive remediation at DOE sites. Science 303, 1615–1616.
[61] Winslow, L.A., J. Read, R. Woolway, J. Brentrup, T. Leach, J. Zwart, S. Albers, and D. Collinge. 2019. rLakeAnalyzer: Lake Physics Tools." R package version 1.11.4.1, https://CRAN.R-project.org/package=rLakeAnalyzer.
[62] Zaret, T.M., Paine, R.T., 1973. Species introduction in a tropical lake. Science 182, 449–455.