A Comparison of Aquaculture Production Methods for Optimizing Production of Fingerling Yellow Perch (*Perca flavescens*)

Cathleen M. Doyle, David A. Culver, Morton E. Pugh, and Jesse E. Filbrun

Abstract Yellow Perch aquaculture has increased since the 1980s to reverse declines in wild populations and meet increased demands by anglers. Over the past 41 years, staff at the St. Marys State Fish Hatchery (SFH) in western Ohio used different methods to obtain Yellow Perch eggs, support embryonic development and hatch eggs, and rear the fry in ponds to the fingerling stage for stocking. We used hatchery records from 1977 through 2017 to statistically compare production outcomes among various rearing methods including (1) natural vs manual spawning, (2) embryo hatching methods, (3) organic vs inorganic pond fertilization, and (4) fry residence time in ponds before harvest. We found that the most reliable production of Yellow Perch fingerlings consisted of placing hormone-induced females in tanks with males, hatching embryos in Heath trays, and stocking fry in ponds fertilized using liquid inorganic fertilizers. While our study is retrospective, and thus precludes assigning causality to any observed improvements in yield with method changes, adopting these methods at St. Marys SFH has increased harvest density of fingerlings produced from 13 ± 4 to 53 ± 6 fish m^{-2} (mean ± SE).

Keywords Pond fertilization · Fingerling production · Pond management · Yellow Perch

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1 Introduction

Yellow Perch (*Perca flavescens* Mitchill) belong to one of the largest families of fishes (Percidae) in North America (Page and Burr 1991). Except for darters, percids represent important commercial and sport fisheries in the Great Lakes region and are subject to intense harvest pressure (Malison 2003). Since the mid-twentieth century, commercial harvest of Yellow Perch populations in the Great Lakes drastically declined, and recruitment remains low (Lesser and Vilstrup 1979; Craig 2000; Baldwin et al. 2018), yet commercial and recreational demand remains high (Riepe 1998). Therefore, Yellow Perch aquaculture has become increasingly important to enhance wild populations experiencing natural declines in recruitment, establish new populations (Fox 1989; Ellison and Franzin 1992; Mitzner 2002), and/or subsidize the market demand for food fish (Malison 2000).

Although percid aquaculture has been refined for Walleye (*Stizostedion vitreum*) and saugeye (Walleye ♀ × Sauger, *S. canadense*, ♂) (Briland et al. 2015), production results have not been compared for the many available Yellow Perch production methods. Previous studies in Ohio have shown that the timing of pond filling, pond fertilization regimens, and source water quality impact Walleye and saugeye production (reviewed in Briland et al. 2015). Managing ecological parameters associated with plankton dynamics in earthen ponds can increase production and survival of these percids (Tew et al. 2006; Jacob and Culver 2010; Briland et al. 2015).

Yellow Perch egg production and hatching methods differ from other percids. Female Yellow Perch require a “chill period” of a few months during winter for egg development. Spawning occurs in the spring, and fecundity is negatively affected by an insufficient number of cold days during ova development (Hokanson 1977; Farmer et al. 2015). Yellow Perch spawn in the spring when water temperatures reach 8–13 °C, with peak spawning at 10 °C (Nelson and Walburg 1977). As with Walleye and Sauger, Yellow Perch are synchronous spawners, producing one batch of eggs annually, and offer no parental care. Yellow Perch eggs are extruded in skeins of a gelatinous matrix which females then attach to submerged aquatic vegetation, rocks, or woody debris, such as fallen trees (Thorpe 1977; Craig 1987).

Broodstock (parents) for culture can be obtained either from the wild, just before spawning, and held at the hatchery until ready to spawn or purchased from a commercial producer. Broodstock may also be held at the hatchery in outdoor production ponds or indoor tanks. Spawning adults may be kept for multiple years, or new parental fish can be chosen each year, depending on the desired genetic composition of the hatchery recruits. Eggs are obtained from either natural spawning occurring in ponds or manual spawning, which requires egg ribbons to be obtained from females and milt obtained from males. The eggs and milt are dry mixed in a bowl for fertilization to occur (Hart et al. 2006). Hatching is temperature-dependent, and the incubation period ranges from 10 to 20 days (Hinshaw 2006). Hatching generally occurs over 2 weeks (Nelson and Walburg 1977; Hart et al. 2006).

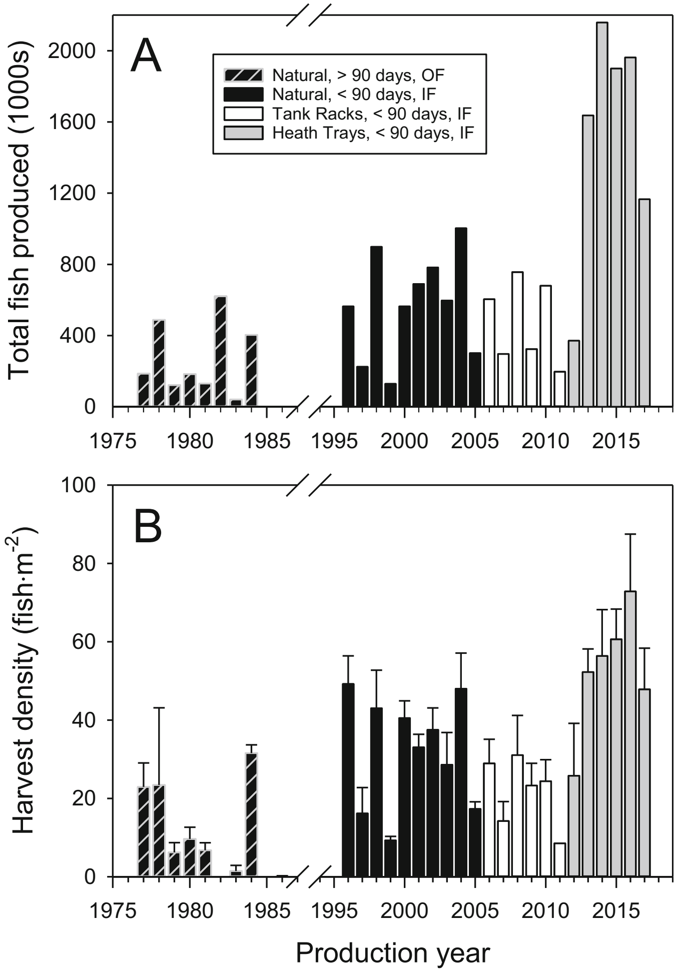

Fig. 1 (**a**) Comparisons of total Yellow Perch fingerlings harvested from ponds at St. Marys State Fish Hatchery from 1977 through 2017. Values are harvest totals summed across all ponds with each year. (**b**) Comparisons of Yellow Perch pond yields through time. Values represent mean + SE of pond yields for each year. Production methods compared are natural spawning versus manual spawning (Tank Racks and Heath Trays), culture duration (<90 days and >90 days), and fertilization regimens (*OF* organic fertilization and *IF* inorganic fertilization)

In this study, we provide a retrospective analysis of historical hatchery data, for Yellow Perch fry and fingerling culture methods by statistically comparing production results for a 41-year dataset (1977–2017) at St. Marys State Fish Hatchery (SFH), Ohio, USA. St. Marys SFH is one of three warmwater hatcheries operated by the Ohio Department of Natural Resources, Division of Wildlife (ODNR-DOW). Yellow Perch culture did not occur every year during the time series, but only when the ODNR-DOW requested fish, and hence production was variable through time

Table 1 Summary of hatchery years, spawning methods, egg incubation methods, fertilizer regimens, and fish residence time in ponds

Period	Years	Spawning method	Egg incubation	Fertilizer	Residence time
I	1977–1984, 1986	Natural	Natural	Organic[a] (OF)	>90 days
II	1996–2005, 2012	Natural	Natural	Liquid inorganic (IF)	<90 days
III	2006–2011	Manual	Tank Racks	Liquid inorganic (IF)	<90 days
IV	2012–2017	Manual	Heath Trays	Liquid inorganic (IF)	<90 days

[a]OF is a combination of Granular Inorganic + Alfalfa Meal

(Fig. 1a). Hatchery staff archived detailed records of Yellow Perch production providing a valuable longitudinal dataset to compare the effects of different production methods on fish sizes and pond yields at harvest. These hatchery records provide a unique opportunity to examine how management decisions may influence production results. However, we note that our statistical analyses are correlative in nature because we did not control management procedures through time and therefore this study does not represent a designed experiment with controls.

Our study objective was to statistically compare production metrics among distinct periods when hatchery management used different combinations of production methods to produce fingerlings for stocking. Specifically, we tested how harvest metrics varied by (1) egg production methods (i.e., natural versus manual spawning), (2) gamete incubation methods, (3) pond fertilization regimens (i.e., organic versus inorganic fertilization), and (4) length of the pond culture phase (i.e., <90 days versus >90 days). Our questions were: (1) What combination of production methods is best for production of fingerling Yellow Perch?, and (2) Will Yellow Perch respond to fertilization regimens used for other percids, such as Walleye and saugeye? We predicted production of fingerling Yellow Perch would increase with controlled inorganic fertilization in ponds, manual spawning, and a shorter duration of rearing in ponds (Table 1).

2 Methods

2.1 Study Site

St. Marys SFH is located in western Ohio, USA (WGS84: 40.527, −84.418). The hatchery was built in 1913 by the Western Ohio Fish and Game Association as a warmwater hatchery and was dedicated as an Ohio SFH in 1936. It historically produced Largemouth Bass (*Micropterus salmoides*), White Crappie (*Pomoxis annularis*), Common Carp (*Cyprinus carpio*), and other species in 51 ponds of various sizes, ranging from 0.11 to 0.85 ha. During 1995–1996, extensive renovations were completed to ponds and the hatchery plumbing system. Thereafter, the hatchery contained 26 ponds of more uniform sizes. Most production ponds are 0.35 ha (0.86 acres) with a mean depth of 1.3 m (pond volume = 4515 m^3). After the renovations, the hatchery produced Walleye, saugeye, Yellow Perch, Fathead Minnow (*Pimephales promelas*), Channel Catfish (*Ictalurus punctatus*), and Blue Catfish (*I. furcatus*).

The hatchery draws hypereutrophic water from the bottom of the adjacent shallow (mean depth = 1.6 m) Grand Lake St. Marys reservoir to gravity-fill all grow-out ponds. The water is filtered through 0.5-mm screens to prevent undesired fish eggs and larvae from entering the ponds. Zooplankton and phytoplankton, however, pass easily through the screens. These screens have been used by all Ohio SFHs for many years, allowing for the regular development of zooplankton without the introduction of wild fish. Originally, the hatchery raised Yellow Perch from eggs to fingerlings exclusively in the outdoor ponds, but the construction of 3 m^3 indoor tanks fed by flow from the wells enabled managers to produce gametes and fry indoors, allowing them to stock known numbers of fry in ponds. The hatchery now contains indoor tanks for producing and hatching eggs of Walleye, saugeye, and Yellow Perch, plus the outdoor ponds for rearing fry to harvestable fingerlings. Over 2010, 2011, and 2014, four wells were drilled (maximum flow of 2.65 m^3 min^{-1} per well) to provide flow-through water for incubating gametes in the indoor tanks at 12 °C, stabilizing hatching dates and providing high-quality water for incubation.

2.2 Production Dataset

St. Marys SFH produced Yellow Perch in 34 of 41 years from 1977 through 2017 (1977–1984; 1986; 1990–1992; 1996–2017). Researchers at The Ohio State University performed experiments with Yellow Perch ponds during 1990–1992 for other projects, so we excluded those years for all analyses, leaving 31 production years in the dataset. In each year, staff maintained records of all production metrics, including pond areas and volumes, numbers of adult pairs stocked into ponds (for years with natural spawning), numbers of fry stocked into ponds (for years with manual spawning), fish residence time in ponds, numbers of fingerlings harvested from ponds, total fish weight at harvest, and average fish total length at harvest. We also calculated average fish weight at harvest (g $fish^{-1}$), fish harvest yields (fish m^{-2} and kg ha^{-1}), and percent survival to harvest (for years with manual spawning).

2.3 Broodstock Management

Yellow Perch broodstock originating from Lake Erie were maintained in two or three winter holding ponds accompanied by advanced yearling perch (future broodstock). Adult broodstock were typically used for several years and were supplemented by adults obtained from commercial breeders when wild-caught broodstock did not meet the needed numbers of adults used for spawning. A formal plan to minimize the effects of inbreeding depression on fish production characteristics has never been used at St. Marys SFH for Yellow Perch production. However, new broodstock were regularly introduced through time to produce embryos. Moreover, hatching success and fry production increased, not decreased, through time, suggesting there were likely no genetic limitations related to fish production. In October, all potential brood fish were placed in tanks containing pond water and 0.5% NaCl and treated with formalin at a rate of 100 ml m^{-3} for 0.5 to 1.0 h, as recommended, to shed any parasites (Hart et al. 2006). Tanks were provided elemental oxygen and mixed during formalin treatments. Fathead Minnows were stocked in each pond as forage for Yellow Perch (510–770 kg ha^{-1}) after first receiving the same prophylactic treatments. Oxygen levels in ponds were monitored weekly to assure they remained normoxic (at or above 8 mg L^{-1}). If they became hypoxic or if ice formed on the ponds, air was injected at the bottom of each pond using compressors to maintain adequate oxygen concentrations.

2.4 Gamete Collection and Incubation

Staff at St. Marys SFH used different methods to obtain gametes over the years. Initially, natural spawning was used for obtaining fertilized eggs, which were produced in ponds (1975–2005). Different densities of mature parental fish were stocked into ponds to spawn, with slight variations year to year due to broodstock availability and differences in pond sizes. As outlined in Briland et al. (2015), an even number of male and female Yellow Perch were stocked at either a low density (<60 parental fish ha^{-1}), a medium density (60–100 parental fish ha^{-1}), or a high density (>100 parental fish ha^{-1}), as early as 10 March, to as late as 13 April (depending on the pond water temperatures). Ponds were filled with water from Grand Lake St. Marys one day before stocking parents, and dead conifer trees (burned to remove needles) were added to ponds for females to attach egg skeins. Spawning is influenced by both temperature and photoperiod (Hart et al. 2006). Parents were removed by seining once egg skeins were observed to avoid predation on fry. Although the natural spawning method involves a relatively small amount of labor by the staff prior to frequent pond fertilization to support zooplankton to feed the fry, there is no control of when fish spawn, when eggs hatch, or the number of fry produced. Weather influences pond temperatures, altering the time from spawning to fry hatching dates. Thus, there is no control over the number of fingerlings collected at harvest, and percent survival of fry to harvested fingerlings cannot be calculated.

In 2006, St. Marys SFH managers switched to manual spawning and incubation indoors based on methods developed by researchers at the University of Wisconsin-Madison and Michigan State University (Hart et al. 2006), which improved the control of timing of hatching and allowed the estimation of the numbers of fry stocked in ponds. Broodstock were removed from winter holding ponds in mid-March to prevent spawning in the ponds and moved indoors wherein 200 males and 200 females were placed into holding tanks (3.0–3.8 m^3). Adults were reliably sexed by examining features of the anus and urogenital opening (Malison et al. 2011). Tanks were supplied with well water and maintained at a constant temperature (12 °C). Dissolved oxygen concentrations were maintained at or above 9 mg L^{-1} via gravity filtration through a packed column prior to iron filtration. The water was then passed through sand and gravel filters to remove iron precipitates from the oxygenated water. To synchronize spawning, female Yellow Perch are commonly injected with human chorionic gonadotropin (hCG) (Dabrowski et al. 1996; Hart et al. 2006). At St. Marys SFH, all female brood fish were injected with a constant dose of 0.05 ml Chorulon hCG (50 IU), regardless of size, to minimize stress from handling time. All tanks were covered to prevent fish escape, and egg maturation occurred 3–8 days after injection. No spawning substrate was placed into these tanks, and no air was added because air causes egg skeins to float to the water surface. Egg skeins were deposited on the bottom of the tanks, typically at night. Tanks were checked twice daily, and fertilized spawn skeins were retrieved by coaxing them off tank bottoms with a stick.

To prevent fungal outbreaks and parasite infections while spawning fish are held in tanks, broodstock were provided a salt bath at 7 g NaCl L^{-1} and a Terramycin HCl treatment (20 mg L^{-1}) for 4 h every 2–3 days. During treatment, the water volume in the tank was drawn down to half full, and the water supply was turned off. Aeration was kept running while the treatments were administered, and fish were periodically checked for stress. All spent male and female fish were given this treatment before returning them to holding ponds over the spring and summer.

Two methods of indoor incubation in aerated well water were used at St. Marys SFH. The first method, which we call "Tank Racks," incubated eggs in 3 m^3 tanks with egg skein support racks constructed of polyvinylchloride (PVC) pipe frames and zinc-coated 2.5 cm diameter mesh (chicken wire) (Fig. 2a). Incubating egg skeins with Tank Racks involves keeping the egg ribbons submerged in the water and not allowing the ribbons to touch one another, avoiding fungal infestation, suffocation, and eventual death of the eggs. Each Tank Rack held eight egg ribbons, with about 15,000–20,000 eggs per ribbon. Water flow was set at 80% turnover per hour to prevent metabolite buildup.

The second method, which we call "Heath Trays," used stacks of shallow trays common to salmonid aquaculture (Fig. 2b, c, d). Each stack contained eight 61 × 65 cm Heath Trays that received filtered well water initially at about 8 L min^{-1}, followed by 11 L min^{-1} after embryos reach the eyed stage. Water traveled through the tray system via gravity so that all trays continuously receive water, flowing from

Fig. 2 Comparison of the Tank Racks and Heath Trays used by St. Marys SFH for egg incubation. (**a**) Tank Racks are made with 0.5-inch PVC pipe and wire mesh and are set at a 60° angle with egg ribbons anchored at the top, set between the wire mesh to remain submerged (Photo credit: Mark Pummell). (**b**) Heath Tray stacks at the St. Marys SFH (Photo credit: David A. Culver). (**c**) Each Heath Tray unit consists of eight trays with screens covering the egg ribbons to prevent loss as water flows via gravity from the top tray to the bottom tray (Photo credit: David A. Culver). (**d**) Egg ribbons incubating inside a single Heath Tray (Photo credit: David A. Culver)

the top tray through each consecutive tray to the bottom. Egg ribbons were removed from spawning tanks and staff measured ribbons in a volumetric cylinder, placing 750 ml into each tray. Staff estimated 75 eggs ml^{-1} by counting the numbers of eggs in 10 mL subsamples settled in graduated cylinders, which equates to about 56,250 eggs $tray^{-1}$. During incubation, all white, moribund eggs were removed daily and counted.

Regardless of the manual spawning incubation technique used, once all eggs have been taken and water-hardened for 24 h, a daily prophylactic treatment of Formalin (Parasite-S) is administered via a calibrated peristaltic pump at a rate of 1000 ppm for 15 min to guard against fungal proliferation. These treatments ceased once eyes become visible in the developing embryos.

As the egg skein degrades and the eyes become fully pigmented, the eggs were ready for forced hatching. This is commonly assessed by testing if a small sample of eggs can be forcibly hatched by aggressive finger swirling them in a beaker (Hart et al. 2006). For the St. Marys SFH incubation regimen at 12 °C, the eggs hatched in 11 or 12 days. If the Tank Racks were used, five to eight skeins of the same age were siphoned into a 20 L bucket full of oxygenated well water and vigorously stirred for 20 s using a paint mixer attached to a power drill. The bucket of water containing eggs was weighed before and after the eggs were added to quantify total egg volume. While stirring, a 10 ml subsample was collected, and fry were counted to determine the number of fry mL^{-1} and hence to estimate the number of fry in the bucket. The fry were then stocked into grow-out ponds. If eggs were incubated using Heath Trays, a 1 L volume of eggs (~75,000 eggs) was poured into a 20 L bucket and stirred as above to hatch eggs for stocking into ponds. Egg and fry numbers were estimated consistently by counting the numbers of each in settled volumes of random samples.

2.5 Fertilization Regimens

Yellow Perch pond fertilization regimens can be divided into two distinct periods (Table 1) that were separated by the period of hatchery pond renovations. From 1975 through 1986, a combination of inorganic and organic agricultural fertilizers was added to ponds. Herein, we call this method "organic" fertilization. Staff applied 6:10:4 (6% N, 10% P_2O_5: 4% K_2O) granular Vigoro® fertilizer at a rate of 168 kg ha^{-1} and alfalfa meal at a rate of 112 kg ha^{-1} to each pond weekly. The Vigoro® fertilizer application contained 10.09 kg N ha^{-1} and 7.34 kg P ha^{-1}. The alfalfa meal, at 2.9% N and 0.24% P, contained 3.25 kg N ha^{-1} and 0.27 kg P ha^{-1}. Combined (assuming all the fertilizer and alfalfa meal dissolved), they provided an addition of 13.33 kg N ha^{-1} and 7.61 kg P ha^{-1}, N:P = 1.8 by mass, equivalent to 1034 μg N L^{-1} and 590 μg P L^{-1}, to each pond each week in addition to whatever was already present in the water. This high phosphorus addition to the already high N and P content of Grand Lake St. Marys water promoted the proliferation of toxic cyanobacteria, including *Anabaena*, *Aphanizomenon*, *Microcystis*, and *Planktothrix*, and nuisance filamentous green algae, such as *Hydrodictyon* (Filbrun et al. 2013a). Moreover, using organic fertilization, there were few "edible" algae species available for zooplankton grazing (Helal and Culver 1991; Culver et al. 1993). Organic fertilization also caused high free ammonia and low dissolved oxygen concentrations (Helal and Culver 1991). Free ammonia is highly toxic to Yellow Perch fry and fingerlings (Espey 2003).

During 1996 through 2017, hatchery managers applied liquid inorganic fertilizers of N and P to ponds weekly to restore N:P to levels that promoted growth of a desirable phytoplankton community (Jacob and Culver 2010). Herein, we call this method "inorganic" fertilization. Briefly, inorganic N and P concentrations were measured in each pond weekly. Using these measured concentrations and known volumes of individual ponds, liquid inorganic N (NH_4NO_3 + Urea) and P (H_3PO_4) of measured concentrations were diluted with pond water and sprayed over pond surfaces to restore each pond concentration to 600 μg N L^{-1} and 30 μg P L^{-1} (20:1 N:P by mass). This method decreased the production of cyanobacteria and filamentous green algae and helped increase the concentrations of "edible" algae needed for zooplankton production (Helal and Culver 1991; Tew et al. 2006; Briland et al. 2015). Inorganic fertilization resulted in zooplankton communities dominated by small-bodied cladocerans (e.g., *Bosmina* and *Chydorus*), cyclopoid copepods (e.g., *Diacyclops thomasi* and *Mesocyclops edax*), and rotifers (Briland et al. 2015).

2.6 Fish Residence Time in Ponds Before Harvest

The length of the production phase changed over time corresponding with the fertilization regimen. During 1975 through 1986, fingerlings produced by natural spawning and organic fertilization were cultured in the ponds until fingerlings were harvested in the fall, either September or October (>90 days duration). During 1996 through 2017, after adopting the inorganic fertilization regimen, fingerlings were harvested in June (<90 days duration) (Table 1).

2.7 Fingerling Harvest Methods

For all these methods, fingerling harvest involved draining the ponds slowly through 1 m × 1 m outlet screens equipped with 1 mm mesh screening. Because pond depth decreases away from the outlet, draining forces the fish to move slowly toward the outlet which contains a rectangular, 0.75 m deep × 2 m × 2 m concrete "kettle" from which fingerlings can be dip netted and transferred to a tub resting on a mechanical scale. The fingerlings can then be transferred to another tub and the tare weight of the original tub and remaining water on the scale determined, allowing measurement of the net mass of fingerlings harvested from the pond. Counting the number of fish in a 500 g subsample enabled estimate of the total number and mean individual mass of the fingerlings harvested from that pond.

2.8 Statistical Analyses of Production Metrics

Use of different egg production methods, incubation systems, pond fertilization regimens, and pond durations resulted in four distinct production periods at St. Marys SFH (Table 1). During 1977 through 1984, plus 1986, Yellow Perch were produced by natural spawning in ponds, organic fertilization, and fish reared for >90 days in ponds. During 1996 through 2005, plus some ponds in 2012, fish were produced by natural spawning, inorganic fertilization, and <90 days in ponds. During 2006 through 2011, fish were produced by manual spawning with incubation to hatching using Tank Racks, inorganic pond fertilization, and <90 days in ponds. During 2012 through 2017, fish were produced by manual spawning and incubation to hatching using Heath Trays, inorganic pond fertilization, and <90 days in ponds.

We statistically compared all available production metrics across the four distinct production periods. Production metrics were averaged across ponds within years.

Thus, each production year was treated as a single, independent sample for each production metric. The number of fingerlings harvested from ponds, total harvested fish weight (kg), fish size at harvest (g fish^{-1} and total length, TL), and harvest yield (fish m^{-2} and kg ha^{-1}) were compared across all production periods using one-way ANOVAs or non-parametric Kruskal-Wallis (K-W) tests. K-W tests were used when the production metrics violated the assumption of homoscedasticity, which was determined from Levene's tests. For ANOVAs, Tukey's HSD was used to test for pairwise differences among production periods. For K-W tests, Dunn's post hoc tests were used to determine pairwise differences among production methods after Bonferroni correction for multiple comparisons. Given the large variation among ponds and years, pairwise differences were reported at $P < 0.1$ rather than the more traditional $P < 0.05$. The number of adults stocked into ponds, number of fry stocked into ponds, and the percent survival of fingerlings were each only available for two of four production periods (Table 2). Each of these metrics was compared between periods using independent-samples t-tests. We used SPSS Statistics version 26.0 (IBM, Armonk, NY) for all ANOVAs, K-W tests, post hoc tests, and t-tests.

The size and number of fish produced in the ponds displayed an inverse relationship, whereby a few large fish or many small fish were harvested. We plotted each pond according to the type of spawning, fertilization regimen, and fish residence time before harvest. We plotted the mean individual mass at harvest from each pond against the number of fish harvested from the same pond and performed a breakpoint analysis to identify threshold relationships between individual mass and number harvested using Kolmogorov-Smirnov (2DKS) tests (Garvey et al. 1998).

3 Results

Yellow Perch production from 1977 through 2017 was variable, but generally increased through time (Fig. 1). The most dramatic increase in fish production coincided with the use of Heath Trays to incubate fertilized eggs. Comparisons of production metrics for Yellow Perch across the four production periods are presented in Table 2. First, we present overall differences in production across the four distinct production periods. Second, we explore competition-based relationships between fish harvest densities and mean individual body sizes. Finally, we examine relationships between stocking and harvest rates for the periods that used manual spawning.

3.1 Differences in Yellow Perch Production Among the Four Production Periods

Yellow Perch production metrics changed dramatically through time as a result of changing the combinations of production methods (Table 1). Harvest density (fish

Table 2 Comparisons of Yellow Perch production metrics among fish production methods. Values represent mean ± SE. Nonparametric ANOVAs (i.e., Kruskal-Wallis tests) were used for production metrics that violated the assumption of homoscedasticity, which was determined from Levene's tests. Significant differences ($P < 0.1$, adjusted for multiple pairwise comparisons) among methods are indicated by different superscripts

Production metric	Natural spawning in ponds, >90 days in culture, organic fertilization	Natural spawning in ponds, <90 days in culture, inorganic fertilization	Manual spawning using tank racks, <90 days in culture, inorganic fertilization	Manual spawning using heath trays, <90 days in culture, inorganic fertilization	Statistical test	*P*-value
Number of production years	9	11	6	6	–	–
Years applied	1977–1984, 1986	1996–2005, 2012	2006–2011	2012–2017	–	–
Number of stocked adults	83 ± 17	36 ± 2	–	–	Indep. samp. t-test	0.028
Number of stocked fry	–	–	273,000 ± 20,000	615,000 ± 86,000	Indep. samp. *t*-test	0.003
Fry stocking density (fry m^{-2})	–	–	78 ± 6	177 ± 25	Indep. samp. *t*-test	0.003
Number of fingerlings harvested	134,000 ± 65,000^{a}	103,000 ± 17,000^{ab}	76,000 ± 12,000^{a}	183,000 ± 22,000^{b}	Kruskal-Wallis Test	0.048
Harvest survival (%)	–	–	28 ± 5	31 ± 3	Indep. samp. *t*-test	0.535
Fish mass at harvest (g $fish^{-1}$)	4.89 ± 1.93^{a}	0.35 ± 0.05^{b}	0.57 ± 0.07^{ab}	0.38 ± 0.08^{b}	Kruskal-Wallis Test	<0.001

Fish total length at harvest (mm)	59 ± 8^{a}	31 ± 2^{b}	38 ± 2^{ab}	31 ± 2^{b}	Kruskal-Wallis Test	0.001
Harvest density (fish m^{-2})	13 ± 4^{a}	29 ± 5^{b}	22 ± 4^{ab}	53 ± 6^{c}	One-way ANOVA	<0.001
Harvest weight (kg)	126 ± 32^{a}	28 ± 4^{b}	36 ± 5^{b}	52 ± 5^{ab}	Kruskal-Wallis Test	0.001
Harvest yield (kg ha^{-1})	168 ± 33^{a}	81 ± 13^{b}	103 ± 13^{ab}	150 ± 15^{ab}	One-way ANOVA	0.014

m^{-2}) was the highest and most consistent when hatchery staff employed Heath Trays to incubate fertilized eggs (Table 2). Using the combination of Heath Trays, a < 90 days culture period of Yellow Perch fingerlings in ponds, and inorganic fertilization (2012–2017), hatchery staff harvested on average 53 $\pm$ 6 fish m^2 from the ponds. By comparison, the other periods produced about one-quarter to one-half of this density. For example, the earliest period (1977–1986), which employed natural spawning in ponds, >90 days in ponds, and organic fertilization, was "boom and bust" in nature. During that time, production among ponds within a single year and production among years were extremely variable. Indeed, the coefficient of variation (CV = standard deviation/mean) for fish harvest density (fish m^{-2}) among years during 1977–1986 was 0.91 as compared to 0.30 during 2012–2017. The two intervening periods had intermediate harvest densities and CVs. These patterns are also reflected in the fish harvest yields (kg ha^{-1}) (Table 2).

Fish body sizes in length and mass at harvest reflect the patterns in fish harvest densities. We observed these patterns throughout our Yellow Perch production time series. During 2012–2017, when hatchery staff employed Heath Trays to hatch eggs, they had a large, steady supply of fry to stock ponds at high densities, resulting in a large number of consistently small (<0.05 g mass ind^{-1}) Yellow Perch fingerlings at harvest (Table 2; Fig. 3a, b, c). By contrast, the largest average fish sizes, but with the most variation among ponds, occurred during 1977–1986 (Fig. 3a, b). Yellow Perch fingerlings sizes at harvest during the two intervening production periods were most similar to the Heath Trays period (i.e., 2012–2017), having consistently small body sizes in length and mass (Fig. 3a, b).

Fish survival could only be compared between the Tank Racks period (2006–2011) and the Heath Trays period (2012–2017), when known numbers of Yellow Perch fry were stocked into ponds. There were no differences in fish survival between these periods, with average survival around 30% (Table 2). It is noteworthy that increasing fry stocking densities during 2012–2017, which was possible because of higher fry yields hatched from Heath Trays, did not reduce fish survival, nor did it appreciably reduce size at harvest in length or mass. In other words, switching from Tank Racks to Heath Trays led to a linear, proportionate increase in fish harvest densities without sacrificing fish sizes at harvest.

3.2 Relationships Between Yellow Perch Harvest Densities and Mean Individual Body Sizes

We sought to further explore relationships between fish harvest densities and fish sizes at harvest to identify production thresholds for managers. Identifying statistical breakpoints in our dataset provides managers a working model of how different ranges of harvest densities can result in fish harvests of different body sizes. For example, managers who desire the largest numbers of fish at harvest should use adequately high fry stocking densities to produce smaller fish sizes with limited

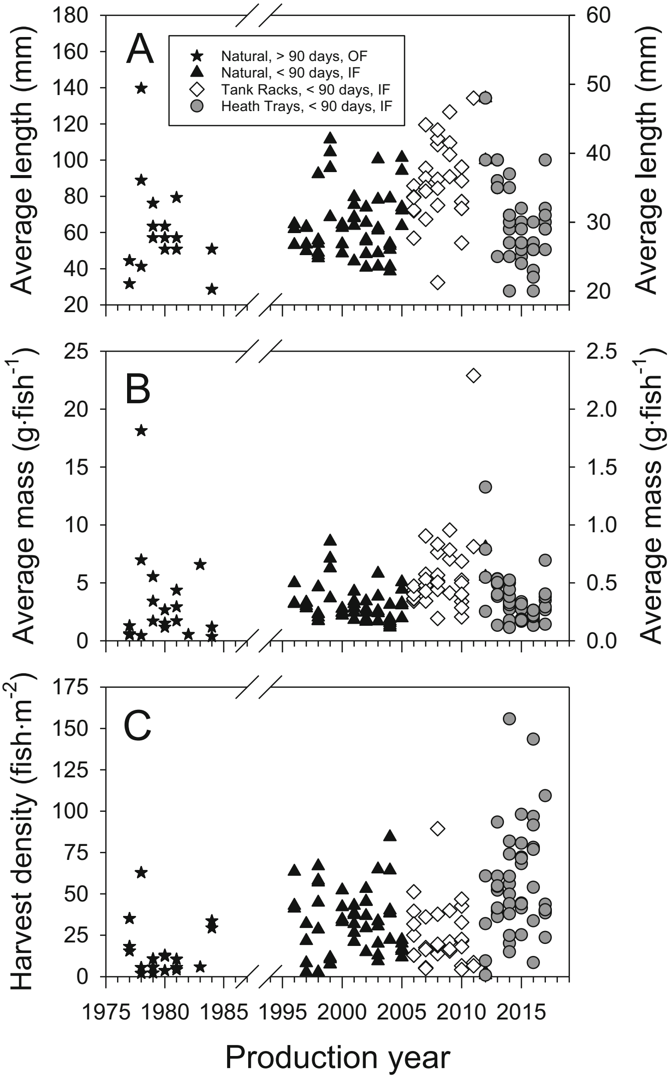

Fig. 3 Comparisons of Yellow Perch fingerling (**a**) total lengths (mm), (**b**) average individual mass (g), and (**c**) densities (fish m^{-2}) at pond harvest. Symbols represent values for individual ponds in each year. Note that fish lengths and masses are scaled differently before 1985 (left *y*-axis) as compared to after 1995 (right *y*-axis), because fish sizes were much larger during the earlier period. Production methods compared are natural spawning versus manual spawning (Tank Racks and Heath Trays), culture duration (<90 days and >90 days), and fertilization regimens (*OF* organic fertilization and *IF* inorganic fertilization)

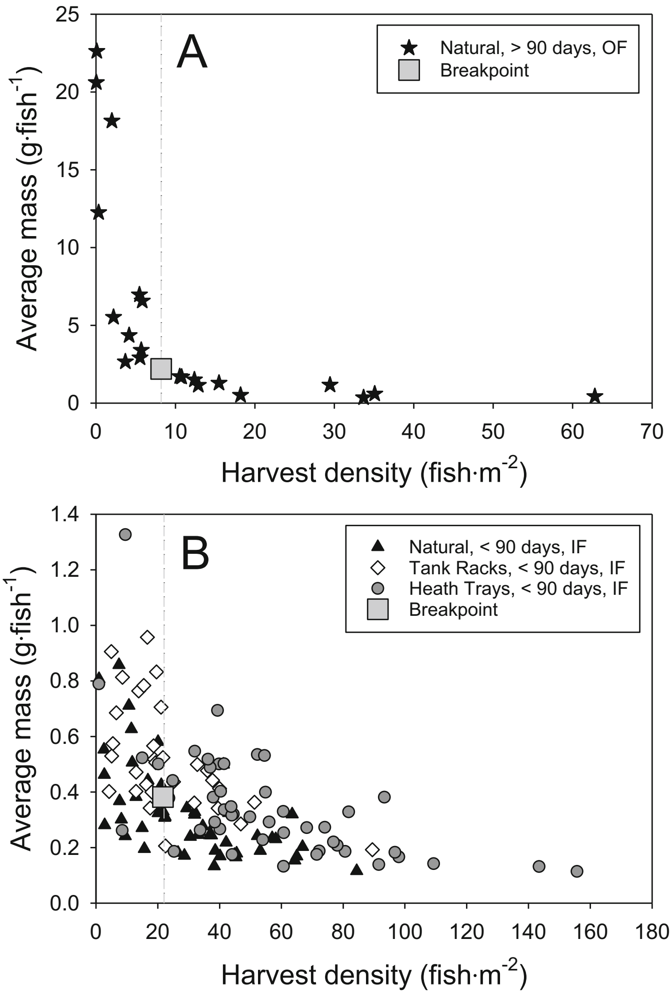

Fig. 4 Relationships between Yellow Perch fingerling harvest density (fish m^{-2}) and average individual size at harvest (g $fish^{-1}$) among production periods. Note that panel **a** presents the relationship for the early period of "natural spawning, >90 days in ponds, organic fertilization (OF)" separate from the other three periods (in panel **b**), because harvest densities were much lower and fish sizes at harvest were an order of magnitude larger during that early period. Each symbol represents results from an individual pond. Breakpoint (BP) symbols are shown to illustrate the two-dimensional (2D) breakpoints as determined using 2DKS tests. Note that panel B presents the 2D breakpoint for all three <90-day production periods combined and all using the inorganic fertilization (IF) regimen

individual growth imposed by intraspecific competition within ponds. We used 2DKS tests to identify significant breakpoints in these production metrics.

There were significant breakpoints between Yellow Perch harvest density (fish m^{-2}) and average mass of individual fish at harvest during all production periods

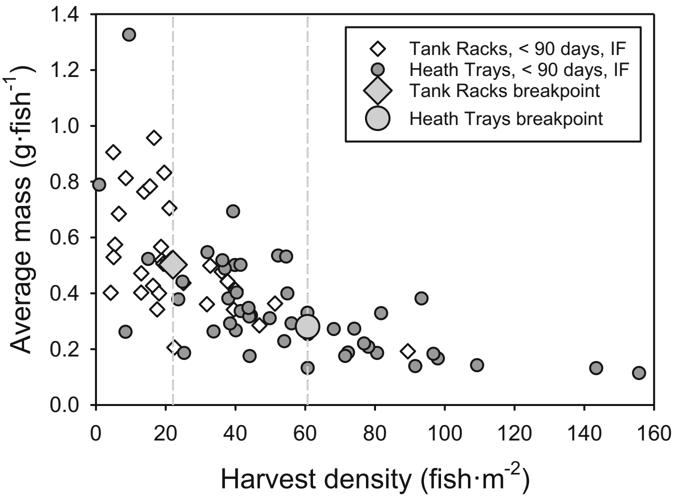

Fig. 5 Comparison of 2D breakpoint relationships between Yellow Perch harvest density and size for fish produced using Tank Racks versus Heath Trays. Each symbol represents results from an individual pond. Breakpoint (BP) symbols are shown to illustrate the two-dimensional (2D) breakpoints for each production method as determined using 2DKS tests (*IF* inorganic fertilization)

(Fig. 4a, b). During 1977–1986, ponds with harvest densities >8 fish·m^{-2} produced fish with individual mass <2.2 g (2DKS test; $D_{BKS} = 0.25$, $P < 0.001$; Fig 4a). Beginning in 1996, liquid inorganic N and P fertilization was adopted, and fish were harvested after <90 days in ponds. During the three production periods starting in 1996, ponds with harvest densities >22 fish·m^{-2} produced fish with individual mass <0.4 g ($D_{BKS} = 0.13$, $P < 0.001$; Fig. 4b). We also examined differences in these breakpoint relationships between the manual spawning methods of Tank Racks and Heath Trays (Fig. 5). During the Tank Racks period (2006–2011), ponds with harvest densities >22 fish·m^{-2} produced fish with individual mass <0.5 g ($D_{BKS} = 0.16$, $P = 0.001$). By comparison, during the Heath Trays period (2012–2017), ponds with harvest densities >61 fish·m^{-2} produced fish with mass < 0.3 g ($D_{BKS} = 0.16$, $P < 0.001$). Note that during the Heath Tray period, average individual fish mass at harvest was consistent all the way up to harvest density of nearly 160 fish m^{-2} still producing fish with mass of about 0.1 g (Fig. 5).

Managers can use our breakpoint results to achieve the desired individual size of harvested fingerlings and harvest densities by adjusting fry stocking densities. The analyses showed that individual mass at harvest declines more rapidly before the breakpoint, whereas individual mass declines relatively little after the breakpoint, allowing for many more somewhat smaller fish to be harvested.

3.3 Relationships Between Stocking and Harvest Rates Using Tank Racks and Heath Trays

We identified a positive linear relationship between the density of fry stocked into ponds and the fingerling harvest density for the production periods that used Tank Racks and Heath Trays (Fig. 6). There was no difference in the slope of the relationship between methods (i.e., survival; ANCOVA, stocking density × production method, $P = 0.28$). Stocking the highest densities of Yellow Perch fry into ponds hatched from Heath Trays had the highest returns of harvested fingerlings.

4 Discussion

Yellow Perch aquaculture has increased over the past four decades to supplement declines in wild populations and meet increased demands by anglers. As hatchery managers have been asked to keep up with the numbers of fingerlings requested by state agencies and grow-out facilities, new methods have developed over the years to help managers achieve these demands. We had the advantage of a 41-year, detailed, and unique longitudinal dataset of Yellow Perch production records from St. Marys SFH to analyze different production methods used over time and to help determine the best methods to produce Yellow Perch fingerlings to stock into reservoirs.

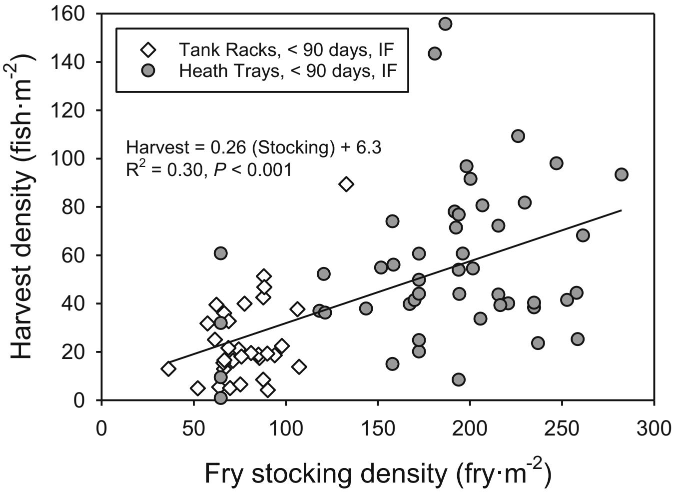

Fig. 6 Relationship between the number of Yellow Perch fry stocked into ponds and the number of fingerlings harvested from ponds using both the Tank Rack and Heath Tray production methods. Note the linear relationship between the numbers of fish stocked and harvested across the entire range of stocking densities. The slope of the best fit line is shown, with the slope representing overall survival for these methods of about 25% survival to harvest

Variation in Yellow Perch production among years resulted from differences in numbers of fish for stocking requested by the managers of the many state reservoirs, methods of fry production, pond fertilization techniques, and occasional excessively low pond temperatures occurring after fry were stocked in the ponds (Mort Pugh, St. Marys SFH manager, personal communication). Although our dataset does not have a typical statistical design and does not represent causal results from controlled experiments, we can draw conclusions from the comparisons between fry production methods, fertilization regimens, and culture duration in the ponds that may be used as guidelines to hatchery managers to increase fingerling production relative to their own facilities.

We observed a shift in fry production methods from natural spawning to a more controlled system of manual spawning, which decreased the variability in size of fingerlings at harvest, as all fry stocked into culture ponds occurred on the same day and with cohorts that hatched at the same time. Producing Yellow Perch eggs naturally is the least desirable method of egg production due to the variability of hatching, numbers produced versus harvested, and the possibility of cannibalism by early hatching fry on late hatching fry (Hart et al. 2006). The staff at St. Marys SFH used a modified method to manually spawn and incubate fertilized eggs. Instead of physically stripping eggs from females, St. Marys SFH staff allowed females to spawn in tanks after hCG injections, making this method less labor-intensive as eggs were fertilized in the tanks instead of dry-mixed in a bowl as Hart et al. (2006) suggest. This also decreased the risk of harming the eggs and female fish. Further, it was possible to calculate the survival of fingerlings in ponds by comparing the number of fingerlings produced with the number of fry stocked in the ponds. We found St. Marys SFH produced more fry when using Heath Trays as compared to Tank Racks. We also found that an increase in fry stocked using Heath Trays produced many more fingerlings, albeit at a smaller size, without affecting percent survival. Heath Trays require less physical labor than Tank Racks throughout the incubation period and are thus preferred by managers at St. Marys SFH. Thus, the system can be leveraged to increase fry density in ponds and still have stockable-sized fingerlings to stock into reservoirs or for feed training.

Inorganic pond fertilization regimens reduced variability in production while increasing survival and yield (Hartleb et al. 2012). Inorganic fertilization has worked well at St. Marys SFH despite the very high nutrient content of its reservoir water. Upon filling, inorganic N concentrations in the ponds could be as high as 1100 μg N L^{-1}, so only an appropriate amount of H_3PO_4 was added that week. N concentrations typically decreased to below the 600 μg N L^{-1} target by 2 weeks later. The three Ohio warmwater hatcheries differ greatly in the nutrient content of their ponds upon first filling (St. Marys SFH >> Hebron SFH > Senecaville SFH) due to the variation in the fertility of their source water reservoirs. These results emphasize the importance of measuring the N and P content variation from pond to pond and week to week prior to calculating the appropriate amount of liquid N and P fertilizers to add. As percid hatcheries occur across the Great Lakes region, with differing source waters, we realize that there is no set concentration to apply to every hatchery; thus each hatchery must identify its own N and P regimens that are most beneficial for avoiding poor water quality conditions (e.g., low DO concentrations, blooms of cyanobacteria and filamentous algae) while promoting zooplankton production.

Hartleb et al. (2012) summarized effects of organic nutrients on pond water quality, including low DO, yet also discussed problems of accumulation of organic matter on the bottom of ponds. Organic matter may promote invertebrate habitat, but this has not been experimentally tested. Wu and Culver (1992) found that Yellow Perch diets shifted from zooplankton to invertebrates (such as chironomid larvae and pupae) when zooplankton densities were less than 10 ind L^{-1} and fish were at least 50 mm TL. However, all fingerlings were harvested <50 mm TL during the Tank Rack and Heath Tray periods at St. Marys SFH. Although organic matter may be beneficial in plastic-lined ponds to promote invertebrate habitat, we caution that adding large additions of organic matter to ponds causes severe water quality issues. For example, Filbrun et al. (2013b) found that commercial feed added to earthen catfish ponds did not enhance invertebrate abundance but caused hypoxia formation and overgrowth of nuisance filamentous algae.

After adopting the inorganic fertilization regimen and decreased culture duration (<90 days) (1996–2017), fish length was more consistent across all years and spawning methods. When fingerlings were reared in ponds for >90 days, zooplankton decreased, and Yellow Perch switched their diets to benthos, yet there is an insufficient supply of prey available in ponds to support growth (Briland et al. 2015). This can contribute to low survival and/or cannibalism. Long culture duration (>90 days) resulted in larger Yellow Perch fingerlings, yet lower densities at harvest. Shorter culture duration (<90 days) resulted in significantly higher harvest densities, though smaller fish.

Aquaculture production datasets generally reveal an inverse relationship between fish harvest density and individual fish size at harvest, reflecting the intensity of intraspecific competition in ponds. Less-intensive production methods and those associated with high mortality rates generally produce few, large fish at harvest. Reduced fish densities increase individual growth rates as competition for limited food resources in ponds is relaxed.

Revisiting our questions, first, if smaller fish are acceptable to managers, then using manual spawning in tanks, with incubation of eggs in Heath Trays, and an inorganic fertilization regimen for <90 days culture duration should produce the most fingerlings to stock into reservoirs or begin to feed train as food fish. Second, we have shown that Yellow Perch do respond to the same fertilization regimen used for other percids (Walleye and saugeye) and variability in production is likewise reduced.

We recognize all hatcheries differ in their source water, water quality and pond sizes, and production goals. Our comparisons may help hatchery managers identify appropriate production methods relative to their own site-specific goals. Accordingly, we have provided an overview of how spawning methods, gamete incubation methods, pond fertilization regimens, and fish residence time in the ponds impact production metrics.

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