fishes

Review

A Decade in Review: Alaska's Adaptive Management of an Invasive Apex Predator

Kristine Dunker [1,*], Robert Massengill [2], Parker Bradley [3], Cody Jacobson [3], Nicole Swenson [4], Andy Wizik [5] and Robert DeCino [2]

1 Alaska Department of Fish and Game, Anchorage, AK 99518, USA
2 Alaska Department of Fish and Game, Soldotna, AK 99669, USA; robert.massengill@alaska.gov (R.M.); robert.decino@alaska.gov (R.D.)
3 Alaska Department of Fish and Game, Palmer, AK 99645, USA; parker.bradley@alaska.gov (P.B.); cody.jacobson@alaska.gov (C.J.)
4 Tyonek Tribal Conservation District, Anchorage, AK 99501, USA; nswenson@tyonek.com
5 Cook Inlet Aquaculture Association, Kenai, AK 99611, USA; awizik@ciaanet.org
* Correspondence: kristine.dunker@alaska.gov; Tel.: +907-267-2889

Received: 6 March 2020; Accepted: 15 April 2020; Published: 21 April 2020

Abstract: Northern pike are an invasive species in southcentral Alaska and have caused the decline and extirpation of salmonids and other native fish populations across the region. Over the last decade, adaptive management of invasive pike populations has included population suppression, eradication, outreach, angler engagement, and research to mitigate damages from pike where feasible. Pike suppression efforts have been focused in open drainages of the northern and western Cook Inlet areas, and eradication efforts have been primarily focused on the Kenai Peninsula and the municipality of Anchorage. Between 2010 and 2020, almost 40,000 pike were removed from southcentral Alaska waters as a result of suppression programs, and pike have been successfully eradicated from over 20 lakes and creeks from the Kenai Peninsula and Anchorage, nearly completing total eradication of pike from known distributions in those areas. Northern pike control actions are tailored to the unique conditions of waters prioritized for their management, and all efforts support the goal of preventing further spread of this invasive aquatic apex predator to vulnerable waters.

Keywords: suppression; eradication; rotenone; fishery restoration; northern pike; salmon

1. Introduction

Management of biological invasions pose significant conservation challenges across the globe. Invasions of aquatic species, particularly freshwater fishes, can be among the most arduous to manage due to factors such as habitat complexity, impacts to co-occurring species, and conflicts between ecological and socioeconomic needs. Due to global anthropomorphic translocations of fishes, native freshwater fish communities rarely resemble those provided by nature [1,2]. In countless waters, many of these events have resulted in the introduced species becoming invasive in their novel environments [3,4]. Notable examples in North America include Asian carp *Hypopthalmichthys spp.* Bleeker 1860 in the Mississippi River drainage, northern snakehead *Channa argus* Cantor 1842 in the Chesapeake Bay watershed, and widespread prolific illegal introductions of game fishes (i.e., bass, trout, walleye). An iconic freshwater game fish that has been widely introduced outside its native range in North America is the northern pike *Esox lucius* Linneaus 1758, and its introductions are currently threatening native fish assemblages in numerous drainages [5].

Northern pike, hereafter pike, have a native Holarctic circumpolar distribution including northern Europe, Asia, and North America generally above 40° latitude. Illegal introductions of pike have expanded their range in several countries in Europe and Africa, southwestern British Columbia, and throughout the American west including southcentral Alaska. Though most of Alaska falls within the native range for pike, Southcentral Alaska does not have any natural populations [6,7]. Pike generally occupy relatively shallow vegetated lakes, flooded wetlands, low-gradient rivers and backwater sloughs [8].

Pike are opportunistic apex predators that are primarily piscivorous but will also prey on small mammals, waterfowl, amphibians, and invertebrates. Where pike are not a native species, they have the capacity to both directly and indirectly alter freshwater fish communities [9–11], especially in waters providing optimal pike spawning and rearing habitat [5]. An effect repeatedly documented following pike introduction is the population-level loss of economically vital fish species [12,13]. Negative ecological and economic impacts such as these classify pike as an invasive species [14] in waters outside its native range [5].

There are a variety of factors that contribute to the invasion success of pike such as its trophic adaptability [15,16] broad physiochemical tolerances [17–19], high fecundity [19], ability to achieve high populations densities [20,21], and popularity as a fishing commodity [22–24]. Throughout the American west, several non-native populations of pike are now well-established. Ramifications of these introductions include complicating endangered species recovery efforts in the Colorado River basin [25], threatening conservation efforts for salmon populations in the Columbia River basin [26], contributing to declines in bull trout *Salvelinus confluentus* Suckley 1859 and westslope cutthroat trout *Oncorhynchus clarki lewisi* Girard 1856 populations in Montana, Washington, and Idaho [27,28], and causing the extirpation and declines of many salmonid populations in southcentral Alaska [5]. The extent of the pike invasion in southcentral Alaska and the resulting consequences to native fish populations in the region have been some of the most extensive in their invaded range. Therefore, the focus of this review will be on the impacts of invasive pike in southcentral Alaska and the on-going adaptive management approaches applied to mitigate the damages.

Data presented in this review originate from a variety of sources spanning from published studies to agency reports, thus making the latter more broadly available to the scientific community. Salmon populations in Alaska are assessed in a variety of ways including aerial enumeration surveys, weir and fishwheel counts, sonar estimates, creel surveys, gillnet surveys, foot stream surveys, guide and commercial logbook records, permit reports, and post-season angler surveys. For all trends reported in this review, cited reports include detailed summaries of the methods employed. Pike are most commonly captured through variations of gillnet surveys, and their abundance patterns are measured through temporal Catch Per Unit Effort (CPUE) comparisons or population estimates (i.e., Peterson mark-recapture methods). In most cases, direct impacts of pike on salmonids have been documented through pike diet investigations, bioenergetics models, and fish assemblage comparisons in waters before and after pike establishment. The collection of work presented in this review documents a decade of progress in managing one of Alaska's most challenging biological invasions.

2. Ecological Role of Pike in Alaska

Pike are a native species in northern and western Alaska but do not naturally occur south or east of the Alaska Mountain Range except for a small, isolated, remnant population near Yakutat [29,30] (Figure 1). Natural pike distribution in Alaska is largely the result of geologic barriers during the Late Pleistocene when the majority of southern Alaska was glaciated [31,32]. For approximately 11,000 years, freshwater fish assemblages in drainages in southcentral (SC) Alaska, hereby defined as the region south of the Alaska Mountain Range, developed in the absence of this aquatic apex piscivore [33,34]. Anecdotal accounts suggest that in the late 1950s, pike were first transported by an angler from the Minto Flats in Interior Alaska to the Yentna River drainage in the Susitna River basin. Subsequent unauthorized introductions and pike movements through open waters resulted in their establishment in over 120 lakes and rivers in the Susitna drainage, Knik Arm drainage, Anchorage vicinity, northern Kenai Peninsula and west Cook Inlet drainages from the Threemile to the Lewis Rivers. Pike populations in SC appear to be genetically distinct from native populations in Alaska and exhibit low genetic diversity indicative of small founding populations [35].

Figure 1. Native and invasive ranges of pike in Alaska. Native range in dashed area; invasive range in solid areas.

Pike occupy a top predator niche in all waters they occur in whether native or non-native [9]. In their native range, pike naturally play a pivotal top-down role in shaping freshwater fish assemblages in shallow low-flow habitats with abundant macrophytes [36]. Examples of natural pike-dominated systems in Alaska include the Minto Flats near Fairbanks, the Dall River tributary of the Yukon River, and the Innoko River in western Alaska [37,38]. In SC Alaska, there is a plethora of similar lowland habitat that naturally functions as vital rearing habitat for Chinook salmon *Oncorhynchus tshawytscha* Walbaum 1792, coho salmon *O. kisutch* Walbaum 1792, and rainbow trout *O. mykiss* Walbaum 1792, among other species [35,39,40]. In many of these waters, pike predation on juvenile salmon and trout has led to localized extirpations of their populations [13,16,41]. Pike diet investigations have demonstrated a propensity for predation on soft-rayed fusiform fishes before other, more energetically expensive, taxa such as sticklebacks *Gasterosteus spp.* Linnaeus 1758 and slimy sculpin *Cottus cognatus* Richardson 1836, waterfowl, small mammals, or conspecifics are depredated [15,16,33,42].

There are approximately 70 lakes in SC Alaska that have documented reduced or extirpated salmonid populations [Alaska Department of Fish and Game (ADFG) unpublished]. Perhaps the most significant case study in SC Alaska waters is that of Alexander Creek, the southernmost western tributary of the Susitna River. Historically Alexander Creek supported a Chinook salmon stock that was vital to the local economy and was one of the most popular recreational fisheries in the Susitna basin. Northern pike were illegally introduced to Alexander Lake at the headwaters of the 84,726-hectare watershed in the 1960s, but it took decades for pike to move and establish throughout the 66 km river corridor and connected waters [43]. In this system [39,40,44] and others in SC Alaska [45], long-distance pike movements over a short duration appear to be uncommon, and pike tend to display a high affinity for macrophyte beds, littoral regions, and outlet streams of individual lakes such that it can take decades for new populations to fully occupy suitable habitat within a drainage [44]. In the late 1980's anglers in Alexander Creek began catching pike [46], but they were not detected in lower Alexander Creek until the late 1990s [43]. Prior to this, Chinook salmon abundance followed similar patterns to those in nearby rivers (i.e., Talachulitna River; Figure 2). By the early 2000's, after pike established in lower Alexander Creek, Chinook salmon abundance precipitously decreased below sustainable levels [43,47]. Exacerbating matters, Chinook salmon in Alaska have been in a period of low productivity since 2007 [48]. However, Chinook abundance in Alexander Creek experienced substantially greater decreases relative to proximate rivers without pike (Figure 2), while angler catches for pike increased (Figure 3).

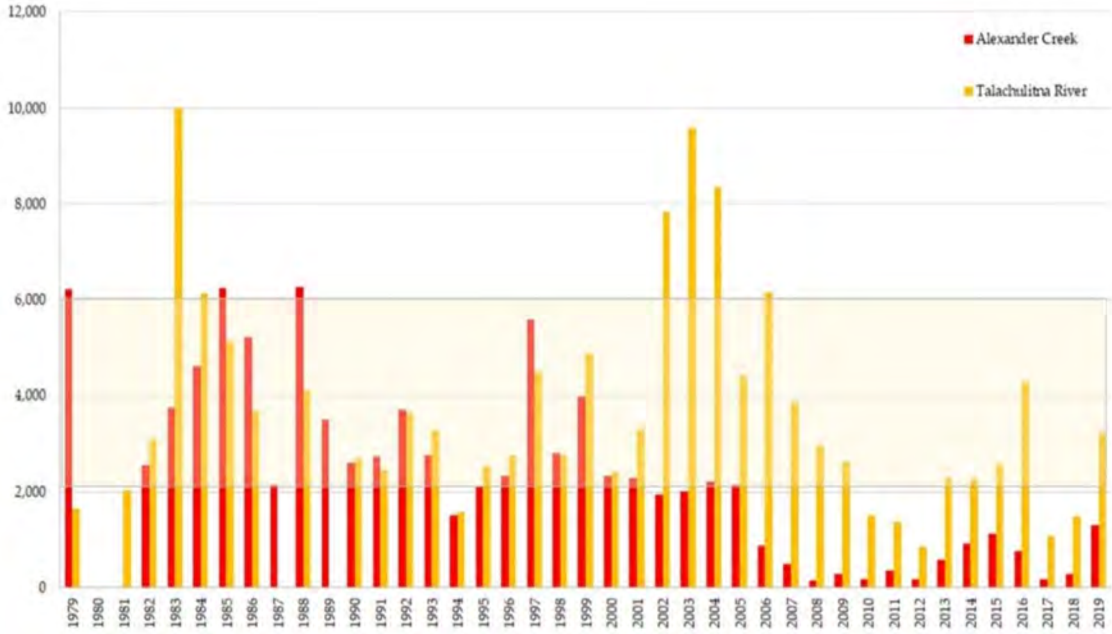

Figure 2. Alexander Creek (pike present) and Talachulitna River (pike not present) aerial survey counts for Chinook salmon escapement. The shaded area shows the escapement goal range (sustainable abundance range) for Alexander Creek Chinook salmon. The escapement goal range for the Talachuitna River is 2200 to 5000 Chinook salmon.

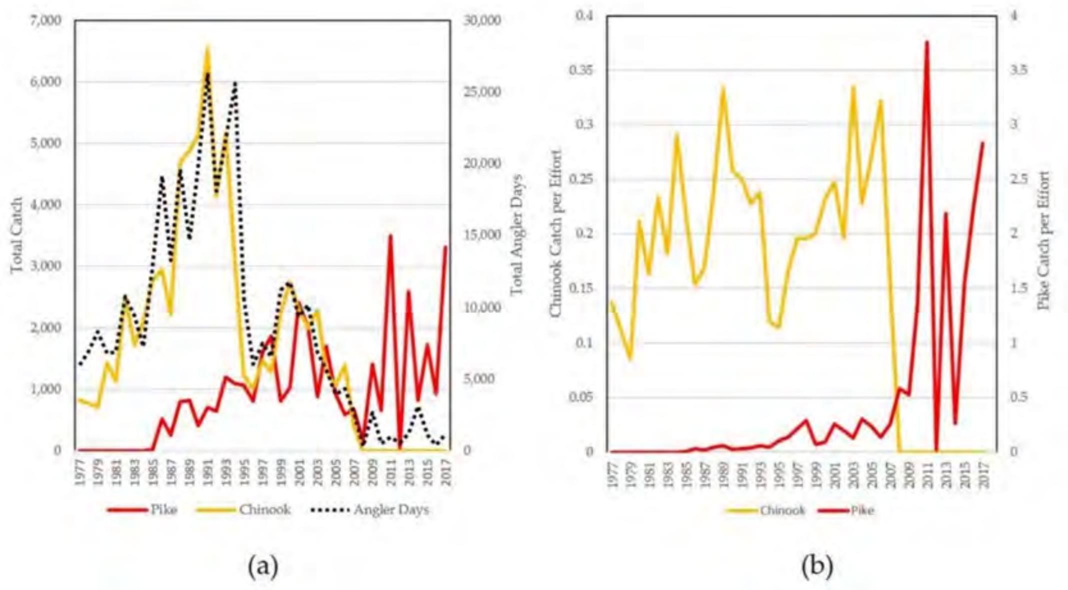

Figure 3. (**a**) Total angler catches of Chinook salmon and Pike in Alexander Creek (1977–2017) based on Statewide Harvest Survey estimates [47,49] and (**b**) Catch per angler effort (angler day) for Chinook salmon and pike in Alexander Creek (1977–2017). Note: Sport fishing for Chinook Salmon was closed in 2008 due to their low returns (Figure 2).

Predation by northern pike is considered the most significant driver of Chinook salmon abundance declines in Alexander Creek [12,16,43]. Pike diet investigations in Alexander Creek began in 2011, about a decade after pike established in the lower river, and their diets reflected the distribution of spawning salmonids, which decreased with distance upstream. In lower Alexander Creek where juvenile salmon were still present but rare, rearing salmon dominated pike diets. Further upstream, where juvenile salmonids had been extirpated, pike diets were dominated by Arctic lamprey *Lethenteron camtschaticum* Tilesius 1811, Pacific lamprey *Entosphenus tridentatus* Richardson 1836 and slimy sculpin, illustrating pike's trophic adaptability following depletion of targeted prey sources [16]. In other SC pike waters such shifts in diet have been shown to eventually deplete secondarily targeted fish species such as threespine sticklebacks *Gasterosteus aculeatus* Linnaeus 1758 [33,34] and eventually become dominated by aquatic macroinvertebrates [41,50]. Bioenergetics models demonstrated that pike could consume up to 1.10 metric tons of juvenile salmonid prey in Alexander Creek annually, which far exceeds the salmonid prey base in the system [12]. This predicted the complete loss of the Chinook salmon stock without management intervention to reduce pike abundance and predation.

The impacts of pike across all SC Alaska waters has been highly variable. This is generally explained by the degree of habitat complexity and connectivity across invaded waters [5,10,16,36]. Where pike are native in western Alaska, they co-occur with the world's largest sockeye salmon *O. nerka* Walbaum 1792 stocks in Bristol Bay. However, large sockeye drainages like the Wood-Tikchick, for example, are enormous systems with deep expansive lakes, high velocity streams, and marshy lowlands. Pike are abundant in littoral regions, marshy lake outlets, and flooded wetland habitats, but are rare in pelagic waters of deep lakes and turbid glacial rivers [51–53]. In drainages like this with a high degree of habitat heterogeneity, salmon may be spatially or temporarily vulnerable to pike predation during parts of their life cycle, but they largely avoid predation otherwise; therefore, the population-level implications for salmon populations are more negligible [16,41]. In drainages where pike are native and have more homogenous habitat with favorable conditions for pike, pike naturally make up a large component of the ichthyofauna in those waters [37,38,54,55].

Where pike are not naturally occurring in SC Alaska, there is similar diversity in habitat throughout the region with areas that are both highly suitable and unsuitable for pike. The Susitna Basin is approximately 6,500,000 hectares, and much of the watershed includes high-velocity clear or turbid glacial rivers, particularly in the eastside Susitna River tributaries. In these waters, pike are unlikely to establish abundant populations nor have significant population-level impacts on salmonid populations because of habitat segregation that mitigates their predation risk. Despite this, the mainstem Susitna River or the Kenai River on the Kenai Peninsula, which do not provide optimal pike habitat, can be used as movement corridors for pike to spread to more favorable habitats. This has been the case in many westside Susitna River tributaries. Westside Susitna streams tend to be lower-gradient, and the surrounding landscape is an extensive interconnected mosaic of lakes, ponds, creeks, marshes and floating bog. Habitat conditions for pike in several westside tributaries are much more favorable, and consequently, pike abundances in these drainages are higher. However, in some cases, westside tributaries with more variable habitat like the Deshka River have high localized pike predation on salmonids, but salmon populations persist because there are areas of the river where salmonids can avoid predation [16]. In contrast, in systems like Alexander Creek that lack predation refugia and have complete habitat overlap between salmon and pike, predation impacts are far greater [16]. This same effect was also observed in over 20 shallow lakes on the Kenai Peninsula [13,56–60]. In waters where habitat conditions favor pike, multiple native fish populations have been lost. Presently, pike remain restricted to only a proportion of their available habitat in SC Alaska, but many drainages and salmon populations remain highly vulnerable to pike invasion [35].

3. Management Approaches

Given the impacts to native fish populations that have already been incurred in SC Alaska and the potential for further impacts, management efforts have been underway to mitigate the damages. Most invasive pike management activities are conducted by or are in consultation with the Alaska Department of Fish and Game (ADFG) and directed through management plans [61,62]. Funding for invasive pike management is limited; therefore, priorities must be identified. Most invasive pike management projects are prioritized using an ADFG-developed scoring matrix designed to ensure that proposed efforts will maximize restoration benefits to impacted fisheries and prevent further invasion of pike to vulnerable waters (Appendix A). The primary functional areas of invasive pike management in SC Alaska include population suppression, eradication, outreach and angler involvement, and research.

3.1. Population Suppression

Population suppression is a common strategy employed for invasive fish management when eradication of an entire population is not feasible [2,25,63,64]. In SC Alaska there are several pike suppression programs in westside Susitna River waters where management is necessary to mitigate impacts to native fisheries, but the spatial extent and reinvasion potential makes successful eradications unlikely with current methods. Current pike suppression programs in the Susitna basin take place in Alexander Creek, Chelatna Lake, Whiskey Lake, Hewitt Lake, Shell Lake and in the Threemile Lake complex and Chuitbuna Lake on the west side of Cook Inlet (Figure 4) [44].

As discussed earlier, the Alexander Creek drainage is one of the most heavily impacted systems in the Susitna Basin, and salmon populations there were predicted to be completely lost without intervention [12]. To prevent this, ADFG conducts an annual program that began in 2011 to reduce pike abundance in the optimal pike habitat of side-channel sloughs along Alexander Creek (Figure 5a). The primary objective is to bolster salmon productivity in the system to sustainable levels [65] by reducing pike predation on juvenile salmon. Each May, during the pike spawning period, gillnets (1.8 m by 35.6 m, variable mesh 1.9 cm–5.1 cm) are systematically fished in approximately 60 sloughs. From 2011–2018, sloughs were fished until they achieved 80% reduction in pike catch from their first day's catch [43]. Beginning in 2019, this method was simplified to fish each slough for three days unless pike continue to be caught, in which case, the slough continues to be netted until pike catches cease [66]. Netting efforts are divided between 2–3 field crews. Due to the remoteness of this area, field crews remain on site for the duration of the season which typically ends by 1 June each year. All pike netted are measured and dissected to study diet patterns, age structure, and sex ratio [43,66]. Co-occurring species distributions and indices of their abundance are monitored through pike stomach contents, gillnet bycatch, and mid-summer minnow trap surveys [43,66]. Annual Chinook salmon returns are monitored through aerial index surveys during the peak of the run that have been flown since 1979 [47] (Figures 2 and 5b). Between 2011 and 2013, pike movements were investigated via radio telemetry to determine if pike at the headwaters of the system in Alexander Lake were a consistent source of fish moving downstream into the creek [44].

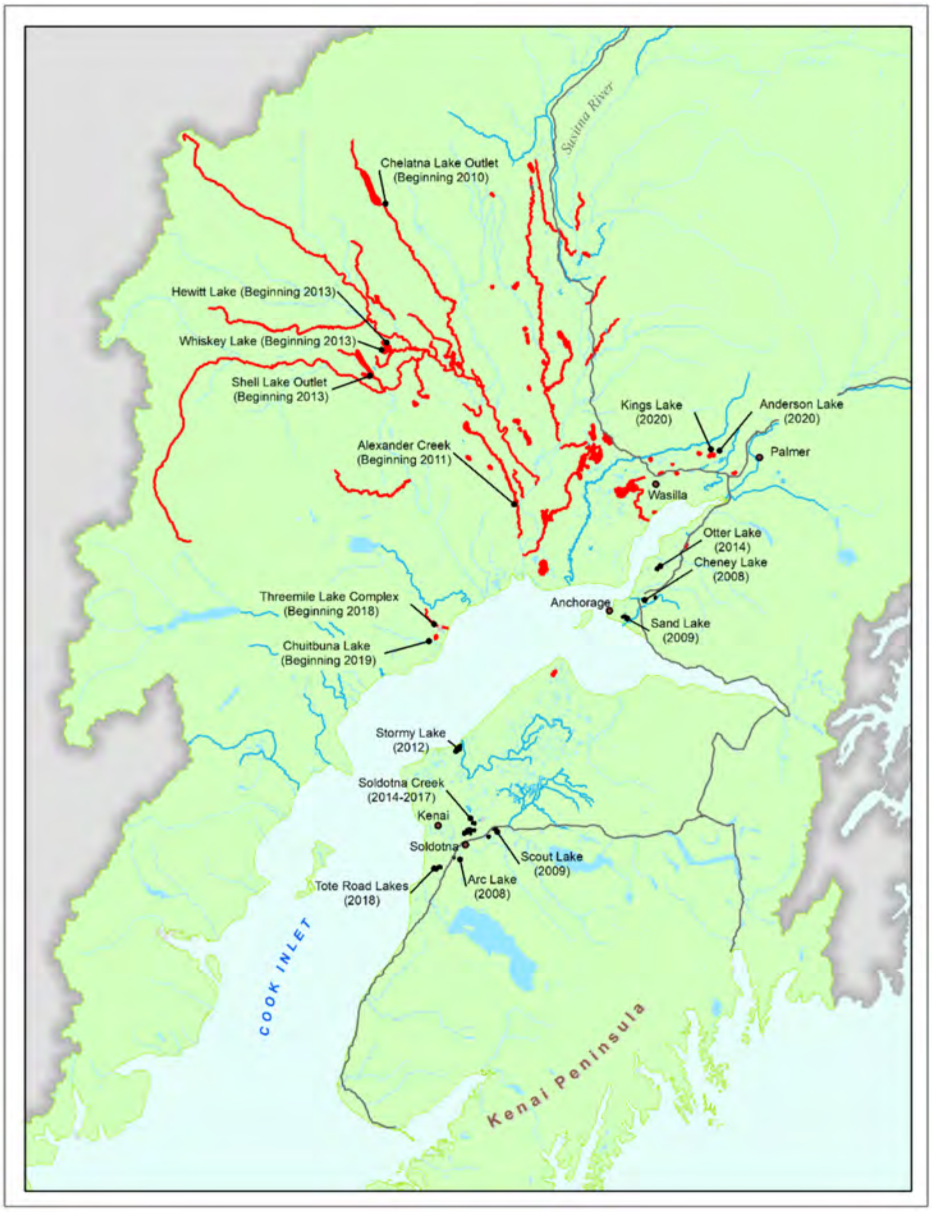

Figure 4. Drainages with pike populations (red). Pike suppression locations noted by year projects were initiated. Pike eradication locations noted by year project was completed.

Between 2011 and 2019, 20,446 pike were removed from Alexander Creek sloughs. During the first three years of suppression between 3000 and 4000 pike were removed annually, but annual pike removal has trended downward since, with less than 1000 pike removed in 2019 (Figure 5b). With the exception of the period between 2016 and 2018, Chinook abundance has trended upward since pike suppression began (Figure 5b). The years between 2016–2018 are difficult to assess because Chinook runs statewide were depressed [48]. However, 2019 saw the largest return of Chinook salmon in Alexander Creek in almost 15 years [65] (Figure 5b). In addition to positive signs with Chinook returns in the system, Chinook distribution has reestablished throughout the entire creek corridor. As discussed earlier, prior to pike suppression, spawning Chinook and juveniles were restricted to the lowest river reach from approximately RM 20.5 to the confluence with the Susitna River (Figure 5c,d). Annual minnow trap surveys, pike stomach analyses, and aerial index surveys confirmed a gradual return of adult Chinook salmon to former spawning grounds and juvenile Chinook salmon reoccurring all the way up to the Alexander Lake outlet by 2014 [43] (Figure 5c,d). In addition, other species like Arctic grayling *Thymallus arcticus* Pallas 1776 and rainbow trout *O. mykiss* Walbaum 1792 have increased in abundance as indicated by gillnet bycatch in recent years. Pike diets in Alexander Creek remain heavily dominated by fish, but despite pike being the dominant fish species in the system, cannibalism was observed in less than 1% of captured pike [43]. During the pike movement investigation in this system, radio-tagged pike displayed a high degree of site fidelity to their tagging locations [44]. Only 7% of tagged pike in Alexander Lake were observed downstream during the study, and all these fish were dispatched in suppression gillnets. At the time, this was interpreted as a positive sign that the objective of increasing salmon productivity in the Alexander system could be accomplished without suppression in Alexander Lake, which would have been a far more costly endeavor. However, in 2014, a new aquatic invasive species, *Elodea canadensis* Babington 1848 was discovered in Alexander Lake. The elodea infestation has rapidly increased and today covers over 90% of the lake [Alaska Department of Natural Resources (ADNR) Unpublished]. While the elodea is under active herbicide management with the goal of eradication, it is unknown if pike movement patterns between Alexander Lake and Alexander Creek have been altered as a result of the significant change in habitat structure. Moving forward, with the current uncertainty in movement dynamics of pike in the system, and to facilitate continued positive trends in Chinook salmon abundance, pike suppression in Alexander Lake is likely now warranted.

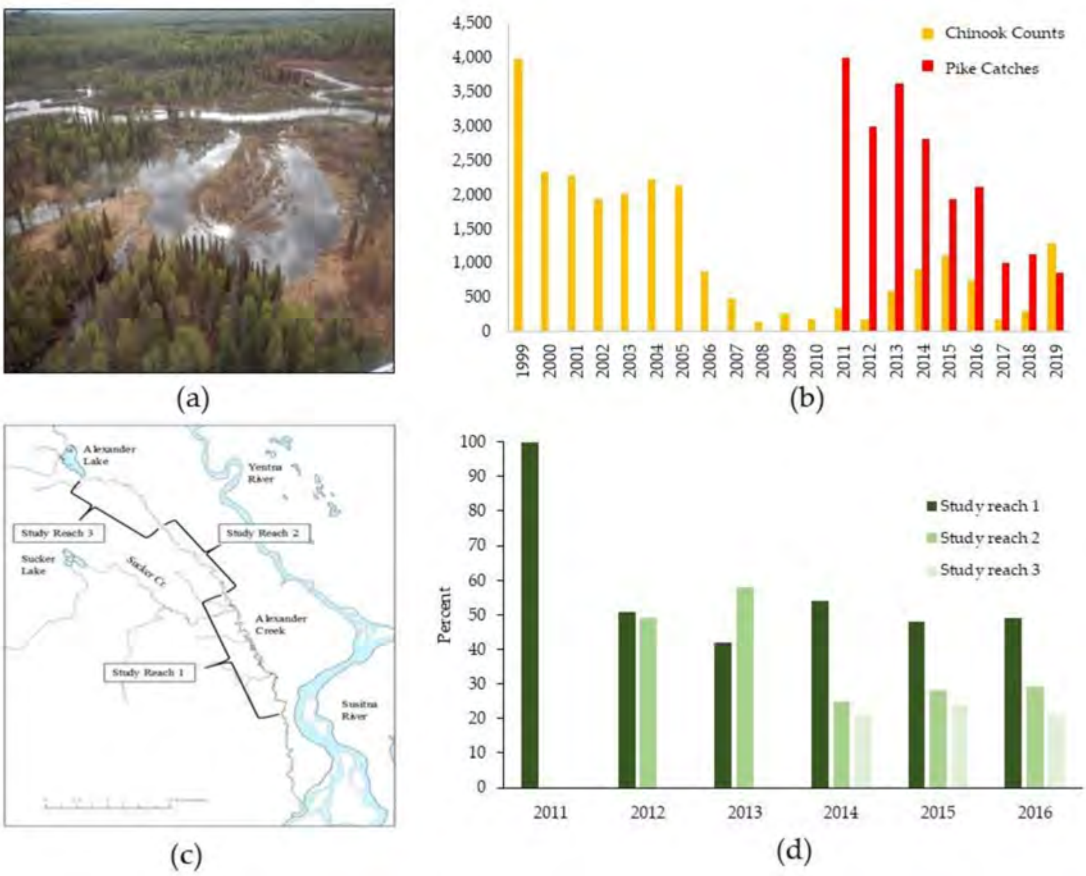

Figure 5. (**a**) A side-channel slough along Alexander Creek, (**b**) 20-year Chinook abundance in Alexander Creek and pike removals by year since suppression began, (**c**) map illustrating study reaches in Alexander Creek (Study Reach 1 = lower Alexander Creek, Study Reach 2 = middle Alexander Creek, Study Reach 3 = Upper Alexander Creek), (**d**) Proportion of juvenile salmon captured in minnow trap surveys in each study reach by year until salmon were again well-distributed throughout the creek corridor (2016).

Pike suppression occurs opportunistically pending funding availability in Shell, Whiskey, Hewitt, and Chelatna lakes and their outlet creeks in a partnership between ADFG and the Cook Inlet Aquaculture Association (CIAA). All these lakes are significant sockeye salmon producers for the Susitna drainage [67]. While some of the lakes, Chelatna in particular, are deep enough to allow habitat segregation between sockeye and pike, sockeye are heavily depredated during both smolt out migrations through outlet streams and juvenile fry recruitment to the pelagic lake habitat. Pike suppression efforts in these lakes have been designed to mitigate these effects [41,68,69].

Natural sockeye production in Shell Lake has declined precipitously since 2007 (Figures 4 and 6). Based on a euphotic volume model, Shell Lake has the estimated potential to contribute up to 10% of the sockeye salmon return to the Susitna River watershed [70]. Between 2006 and 2011, Shell Lake contributed 6.1% of the sockeye salmon return to the Susitna [71]. Due to a notable decline in weir counts of sockeye smolt leaving Shell Lake since 2010 (Figure 6) and a similar trend in adult returns, CIAA initiated pike suppression efforts to reduce predation pressure on smolt. The project included several components including smolt and adult sockeye enumeration, sockeye stocking with Shell Lake brood stock, disease screening, pike suppression, beaver dam modifications, and evaluating the effect of pike suppression on sockeye and pike abundances in the lake.

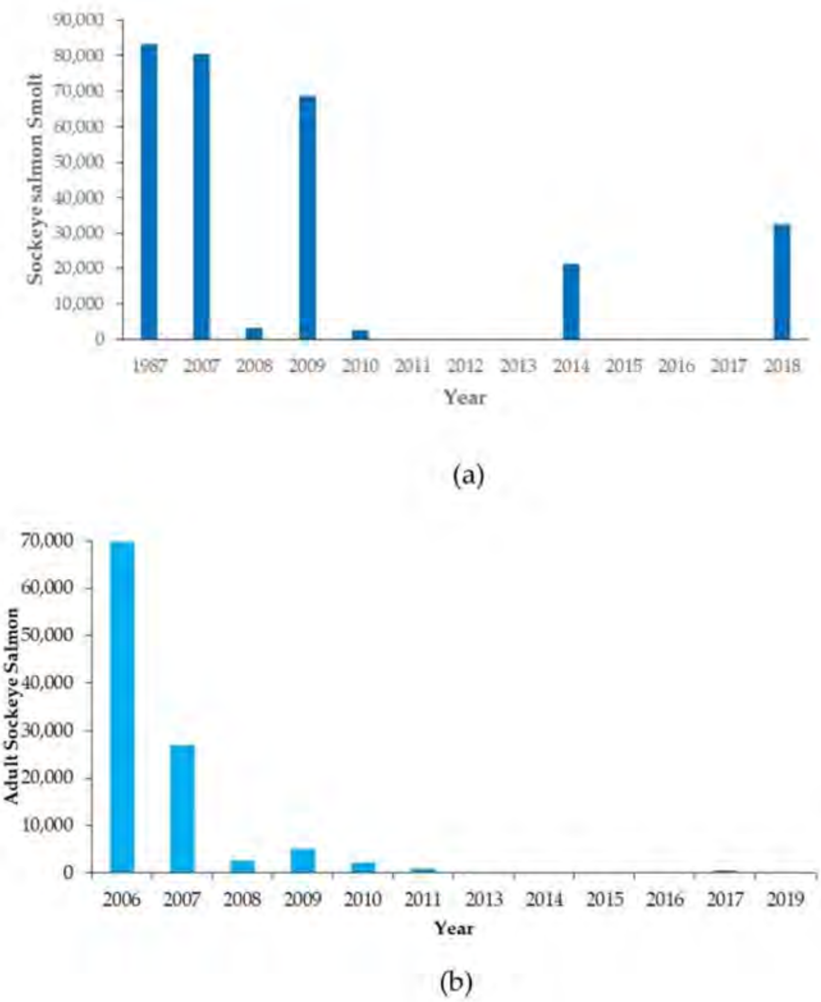

Figure 6. (**a**) Sockeye smolt counts in Shell Lake in 1987 and from 2007–2018 (**b**) Weir counts for adult sockeye in Shell Lake from 2006–2011, 2013–2017, and 2019.

CIAA collected eggs from adult sockeye salmon in Shell Lake during 2012, 2016, and 2017. The fertilized eggs were reared in Trail Lakes Hatchery to the smolt stage and released back into Shell

Lake in 2014, 2018, and 2019. The 2014 smolt release occurred prior to major pike suppression and resulted in the outmigration of only 25% of the released smolt. Diet data taken from captured pike in 2014 showed that the northern pike in Shell Lake stopped preying on most other prey items and focused heavily on smolt when they were available [71–73]. Between 2014 and 2019 CIAA removed 5296 pike from Shell Lake with gillnets (2.5 cm bar gillnets, 2.4 m by 15.2 m) and the number of stocked sockeye smolt emigrating from the lake increased to 71% [73]. Since suppression began, over 7050 pike have been removed from Shell Lake with gillnets reducing the catch-per-unit-effort over that time period from 0.39 pike/gillnet h in 2012 to 0.06 pike/gillnet h in 2019. Bioenergetics models have estimated that this decrease in the pike population reduced the consumption of salmonids by approximately 81% for the period between 2012–2016 [68].

Pike suppression with gillnets (1.8 m by 22.9 m, variable mesh 2.5 cm–7.6 cm) and fyke nets was conducted in Chelatna Lake between 2010–2012 and 2017–2019 by ADFG and intermittently by CIAA between 2009–2016. Like Shell Lake, Chelatna is a significant sockeye producer for the Susitna River but also supports populations of Chinook, coho, chum *O. keta* Walbaum 1792 and pink *O. gorbuscha* Walbaum 1792 salmon. Combined suppression efforts in Chelatna Lake has removed 4335 pike, and CPUE has decreased over time (Figure 7). Pike diet analyses documented that juvenile salmon dominated pike diets during outmigration, sockeye prey size was positively correlated with pike predator size, and 67% of the depredated sockeye smolt were consumed by pike less than 30 cm (fork length). Bioenergetics estimates of sockeye smolt survival resulting from pike suppression activities suggested a potential increase of over 13,000 adult sockeye [74].

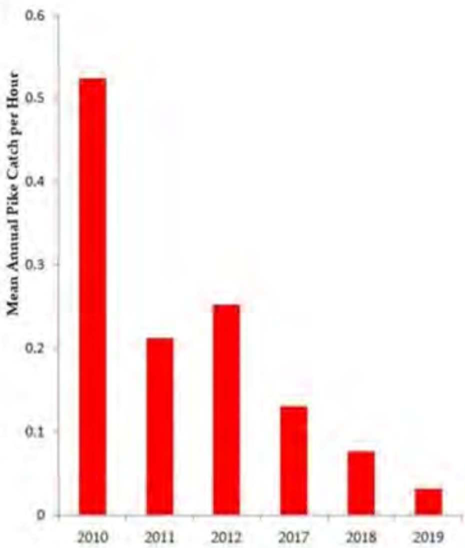

Figure 7. Catch Per Unit Effort (CPUE) of pike removed during ADFG pike suppression in Chelatna Lake 2010–2012 and 2017–2019.

In the Yentna River drainage, pike suppression is conducted in Hewitt and Whiskey lakes and the Hewitt-Whiskey Creek outlet that connects these lakes to the Yentna River (Figure 4). Since Yentna River water backs up into Hewitt Lake during peak summer flows, Hewitt and Whiskey lakes provide rearing habitat for juvenile sockeye salmon produced by adults that spawn in sloughs and tributaries of the Yentna River drainage upstream of these two lakes. Approximately 17–26% of Yentna River sockeye (~48,000–62,000) were estimated to spawn in the upper river based on radio-telemetry investigations [75–77]. Production estimates from a euphotic volume model indicate that Hewitt and Whiskey lakes can support juveniles produced by approximately 51,000 spawners [70]. Since monitoring began in these two lakes, fall fry sockeye salmon abundances in Hewitt Lake declined from 1,105,773 in 2005, to 213,353 in 2006 and 56,161 in 2007 [78]. Sockeye salmon smolt abundances at Whiskey Lake declined from 15,832 in 2012 to 2922 in 2013 and 1395 in 2014 [79]. During this time, pike (>250 mm length) abundances were estimated as 1046 (95% CI: 743–1531) in Hewitt Lake, 3419 (2569–4550) in Whiskey Lake and 3496 (1854–6593) in the Hewitt-Whiskey Creek outlet for a total estimated population of approximately 8000 pike [80]. The relatively high density of northern pike confined to the Hewitt-Whiskey Creek outlet suggests that juvenile salmon suffer high predation mortality while migrating through this system. The goal of current pike suppression is to reduce the pike population in the Hewitt-Whiskey Lake system by 80% over three years. In total, 5087 northern pike from Whiskey Lake were removed between 2012–2019, reducing CPUE from a high of 2.6 pike/gillnet h in 2012 to 0.45 pike/gillnet h in 2019. In Hewitt Lake, 1712 pike have been removed during this period reducing the CPUE from 1.75 pike/gillnet h in 2012 to 0.34 pike/gillnet h in 2019. Assuming a combined population of 8000 northern pike over 250 mm and an average daily individual consumption of one juvenile salmon per day [80] over a summer (150 days), this project is predicted to increase survival of juvenile salmon by approximately 955,000 over three years that would otherwise be depredated by pike. Project success will be evaluated based upon whether hydroacoustic survey estimates indicate the abundance of juvenile sockeye salmon rearing in the system increases by about 1,000,000 by the fall of 2020 [ADFG Unpublished]. The 2018 hydroacoustic surveys estimated populations of juvenile sockeye salmon in Hewitt Lake totaled about 367,000 sockeye fry and, in 2019, the populations of fry increased to approximately 568,000 [ADFG Unpublished].

Finally, in 2018 and 2019, new pike suppression programs were initiated in the Threemile Lake complex and Chuitbuna Lake, respectively, on the west side of Cook Inlet [81,82] (Figures 4 and 8a). These areas are significant because they are at the invasion front of pike in this region. It is presently unknown if these pike populations are the result of illegal anthropomorphic introductions or migrations through Cook Inlet from the Susitna River. Pike are tolerant of low-salinity conditions, and in other parts of their native range, such as the Baltic and Caspian Seas, estuarine habitats can be important migratory corridors [17,83]. In SC Alaska, commercial salmon set-netters occasionally report catching pike in Cook Inlet [ADFG Unpublished]. It is highly feasible that this is now a mode of pike dispersal to west Cook Inlet and, potentially, Kenai Peninsula waters. To investigate this hypothesis further, a new research program between ADFG and the University of Alaska is beginning to analyze pike otolith chemistry to determine origin and utilization of Cook Inlet as a travel corridor [83,84].

The west side Cook Inlet pike suppression sites were conducted in partnership between ADFG the Tyonek Tribal Conservation District (TTCD) and the Native Village of Tyonek (NVT) to increase capacity for pike suppression in a remote region of pike's invaded range in SC Alaska. Alliances between the state, federal agencies, tribal organizations, NGOs, and universities greatly increase resources available for invasive pike suppression and expand the scope of capabilities in the region.

The Threemile and Chuitbuna projects were set up with mark-recapture studies to determine baseline population estimates of pike ≥ 300 mm and assist with long-term evaluation of the pike suppression efforts. In the Threemile Lake complex, which includes Threemile Lake, West Threemile Lake, and Upper Lilly Lake, population estimates in 2018 for pike ≥ 300 mm were 1063 ± 102 (95% CI), 45 ± 11, and 221 ± 70, respectively. In a 10-day suppression event, which doubled as the recapture event, netting efforts reduced those populations by 49% to 57%. A 10-day suppression event in the Threemile Lake complex in 2019 removed a similar number of pike as the previous year. In a 2019 mark-recapture population study for Chuitbuna Lake, the population estimate for pike ≥ 300 mm was 150 ± 13. The suppression event, which doubled as the recapture event, removed 80% of the population in four days of netting. Each lake will be reassessed with mark-recapture evaluations every five years to measure long-term suppression success. It is likely that the similar pike catches in the first two years of suppression in the Threemile Lake complex can be explained by recruitment of pike into the 300 mm size class (Figure 8b). As observed previously, it can take a few netting seasons before catch rates substantially decrease [43] (Figure 5b). Similar to all pike suppression efforts described, pike removed from these lakes are dissected for diet analyses, size class, age, and sex ratio. In addition, over 2000 otoliths have been removed from these pike for use in otolith microchemistry research.

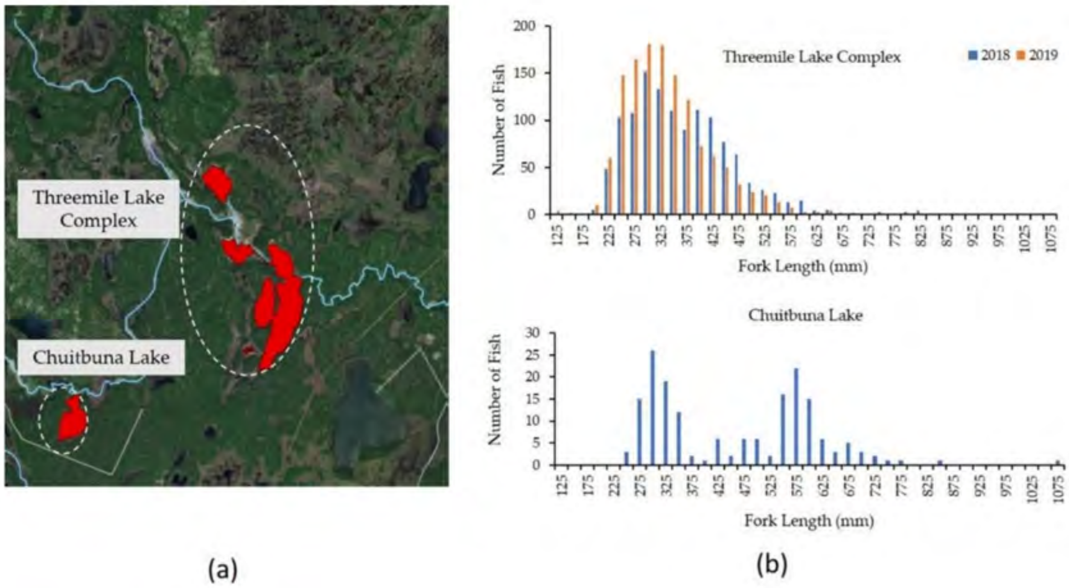

Figure 8. (**a**) Map of west side Cook Inlet pike suppression projects and (**b**) length-frequency distributions of pike removed to date.

3.2. Population Eradication

Although many of the invasive pike management activities in SC Alaska rely on suppression in complex interconnected drainages, the preferred alternative when possible is to eradicate pike populations entirely. This allows for direct restoration of native fish assemblages by removing source populations that could disperse or be introduced to proximate vulnerable waters [85]. At present, there are few management tools that can effectively lead to eradication of invasive fish populations. In rare cases, fish populations from very small lakes can be eradicated with gillnets [86]. In SC Alaska, pike have been eradicated from three lakes on the Kenai Peninsula with intensive winter-long under-ice gillnets (Tiny Lake, Hall Lake and Warfle Lake), but each of these were less than 20 surface hectares, contained low-density populations of less than 30 pike, and juvenile pike catches were low indicating poor recruitment [87]. Besides fortuitous eradications in small lakes with nets, completely draining a waterbody can be another method of fish eradication [85] although this is rarely feasible. This has not been done specifically for pike in SC Alaska, but a pike population in Campbell Lake in Anchorage was eliminated following a municipal project that reduced the water level down to the Campbell Creek thalweg in 2011 [ADFG Unpublished]. The most common method used for invasive fish eradications worldwide is through chemical treatments using piscicides, particularly liquid and powdered formulations of rotenone [88]. Rotenone treatments have been used across the western United States and in SC Alaska for pike eradications [5] (Figure 4).

Rotenone is a naturally occurring compound derived from the roots of tropical plants in the genera *Derris* Graham 1852, *Lonchocarpus* Kunth 1824 or *Tephrosia* Persoon 1807. It has been used for centuries by indigenous cultures in Central and South America to catch fish for food. Rotenone has been used as a piscicide by fishery management agencies in the U.S. since the 1930s to remove unwanted or invasive fish. Currently, rotenone is commercially available as either a wettable-powder or liquid and is registered by the U.S. Environmental Protection Agency (EPA) as a restricted-use pesticide for fish management [89]. Rotenone is lethal to fish because it is readily absorbed through the gills where it instantly enters the blood stream and blocks the biochemical process that allows fish to utilize oxygen during cellular respiration [90]. At the concentrations typically used for invasive fish eradications, the piscicide is not harmful to birds, mammals or adult life stages of amphibians, but is lethal to plankton and macroinvertebrates at varying levels [91]. Rotenone does not enter ground water sources as it is readily bound to organics and, because it is naturally broken down by photolysis and thermal degradation, it generally does not persist long-term in the environment [90]. The piscicidal effects of rotenone can be immediately neutralized with potassium permanganate, and this is typically done when treatment areas include flowing waters.

Decisions to utilize rotenone are strategically made in SC Alaska in waters that will remove important source populations of pike that could spread to nearby vulnerable waters (Appendix A). ADFG completed over 20 rotenone treatments for pike eradication since 2008 (Table 1). To reduce collateral damages, treatments are typically conducted in October just before ice-up. During this time of year, macroinvertebrate populations are seasonally senesced, most piscivorous waterfowl have migrated to wintering areas, and recreational activities for lake residents are less likely to be interrupted. Following all rotenone treatments, water samples are regularly analyzed for degradation rates of rotenone and its byproduct, rotenolone. Under the cold and dark conditions of Alaska's winters, rotenone often remains active throughout the entire ice-covered period [58–60,87]. This is an advantage as it typically ensures sufficient exposure to achieve 100% pike mortality, especially in treatment areas that contain seeps and floating bogs that can be difficult to effectively treat but will freeze solid during the treatment period.

Pike eradication projects for invasive pike in SC Alaska began with small treatments of isolated lakes and later expanded into more complex systems (Table 1). Projects involving rotenone have taken between one to four years to complete. Much of the time investment involves carefully planning and choreographing the treatments, conducting pre-treatment water quality and biological assessments, lake mapping, public scoping, and acquiring state and federal permits (i.e., National Environmental Policy Act. The volume and habitat conditions of each individual waterbody determine the application methods that are employed [58–60,87] (Table 1). Pike eradications in SC Alaska most commonly include rotenone delivery by motorboats equipped with semi-closed pump systems, some specialized for deep water rotenone delivery. Rotenone pumped from an airboat or all-terrain vehicles as well as helicopter spraying, has been used in wetland areas between lakes or along creek corridors. Backpack sprayers, drip stations and rotenone mixture balls are commonly used in small inlet streams, seeps, and difficult-to-treat areas. For treatments requiring deactivation, potassium permanganate is applied at the lake outlets based on flow rates, and sentinel fish downstream are carefully monitored to ensure deactivation is effective [87]. Rotenone treatment success is confirmed through a combination of gillnetting, including under-ice net sets, observations of caged sentinel fish, analytic determination of rotenone concentration achieved and eDNA detection methods [92,93]. Post-treatment, lakes are monitored through routine surveys to ensure pike are not reintroduced [94]. Once rotenone treatments are complete and post-treatment assessments have confirmed successful pike eradication, fisheries are restored to the treated lakes.

Fishery restoration for pike eradication projects is tailored individually based on historical fish assemblages and uses of the treated water body pre-pike introduction. In cases where pike have been removed from lakes that were part of ADFG's Statewide Stocking Plan [95], these lakes are re-stocked with hatchery-produced triploid salmonids. In most pike waters with wild fish assemblages that have been treated, pike and stickleback were all that remained [58,59,87]. However, there are two large projects where native fish were present at the time of treatment, and substantial efforts were undertaken to save their populations.

In 2012, Stormy Lake near Nikiski on the Kenai Peninsula was treated to prevent pike from dispersing into the nearby Swanson River drainage (Figure 4). This lake, due to its depth (17 m), had maintained its native Arctic char *Salvelinus alpinus* Richardson 1836 population and other native species like longnose suckers *Catastomus catastomus* Lesueur 1817. As a precaution, gametes were collected from the char to rear in a hatchery and preserve the genetics of that population. As many native fish as possible were collected prior to treatment and held in a net pen in a nearby lake until the rotenone degraded and these fish could be introduced. From there, natural recolonization of native fishes from the Swanson River further re-established native fish assemblages in the lake.

Table 1. Rotenone Applications for Invasive Northern Pike Removal in southcentral (SC) Alaska.

Year	Water Body	Location	Volume (ha-m) [a]	Quantity [b]	Rotenone Concentration mg/L (Target /Actual)	Detoxification Time	Application Method	Species Reintroduced [c]
2008	Arc Lake	Soldotna	17.8	181.7 L CFT	0.050/0.035	8 months	Boat	SS, ST
2008	Cheney Lake	Anchorage	21.6	219.6 L CFT	0.050/0.030	5 months	Boat, Backpack Spray	RT, GR, SS, ST
2009	Scout Lake	Sterling	103.0	700.3 L CFT + 499.0 kg Powder	0.070/0.030	8 months	Boat, Backpack Spray	RT, GR, SS, ST
2009	Sand Lake	Anchorage	140.4	1348 L CFT	0.050/0.030	7 months	Boat	RT, GR, SS, AC
2012	Stormy Lake	Nikiski	858.3	3444.7 L CFT + 3500 kg Powder	0.050/0.048	4 months	Boat (Weighted Hose), Airboat, Backpack Spray, Deactivation	RT, AC, SS, LS
2014	Union Lake	Soldotna	88.7	327.1 L CFT + 504.8 kg Powder	0.050/0.024	8 months	Boat, Backpack Spray	RT, SS, DV, SC, ST
2014	East Mackey Lake	Soldotna	115.6	424 L CFT + 655.4 kg Powder	0.050/0.026	6 months	Boat, Backpack Spray	RT, SS, DV, SC, ST
2014	West Mackey Lake	Soldotna	150.5	564 L CFT + 902.6 kg Powder	0.050/0.024	8 months	Boat, Backpack Spray	RT, SS, DV, SC ST
2014	Derks Lake	Soldotna	56.4	206.3 L CFT + 226.8 kg Powder	0.050/0.024	6 months	Boat, Airboat, Backpack Spray, Deactivation	RT, SS, DV, SC, ST
2015	Otter Lake	JBER	110.2	1400.6 L. CFT + 22.7 kg Powder	0.050/0.024	4 months	Boat, Airboat, Backpack Spray, Drip Stations	RT
2016/17	Sevena Lake	Soldotna	74.0	605.7 L CFT	0.040/0.036	10 days	Boat, Airboat, Backpack Spray	RT, SS, DVSC, ST
2016	Soldotna Creek	Soldotna	-	191.5 L. CFT	0.040/0.036	5 days	Helicopter, Drip Stations, Backpack Sprayers, ATV, Deactivation	All Species Recolonized from Kenai River
2016	Loon Lake	Soldotna	24.4	111.7 L CFT + 65.8 kg Powder	0.040/0.028	8 months	Boat	RT
2018	Hope Lake	Soldotna	50.1	418.3 L CFT	0.040/0.018	3 months	Boat, Backpack Spray	RT, SS, ST
2018	G Lake	Soldotna	35.0	288.4 L CFT	0.040/0.028	3 months	Boat	RT, SS, ST
2018	Crystal Lake	Soldotna	34.2	279.7 L CFT	0.040/0.040	3 months	Boat	RT, SS, ST
2018	Leisure Lake	Soldotna	15.2	124.2 L CFT	0.040/0.040	3 months	Boat	RT, SS, ST
2018	Leisure Pond	Soldotna	1.4	13.6 L CFT	0.040/0.024	3 months	Boat, Backpack Spray	RT, SS, ST
2018	Fred's Lake	Soldotna	1.9	57.5 L CFT	0.040/0.011	3 months	Boat, Backpack Spray	RT, SS, ST
2018	Ranchero Lake	Soldotna	5.1	42.0 L CFT	0.040/0.024	3 months	Boat, Backpack Spray	RT, SS, ST
2018	CC Lake	Soldotna	33.0	26.9 L CFT	0.040/0.026	3 months	Boat	RT, SS, ST
2020	Anderson Lake [d]	Wasilla	118.4	1211.3 L CFT	0.040/TBD	TBD	Boat	RT
2020	King's Lake [d]	Wasilla	107.6	1100.0 L CFT	0.040/TBD	TBD	Boat	RT

[a] Unit = Hectare-Meters (Imperial conversion = Acre-Feet). [b] CFT—CFT Legumine Liquid Rotenone (Unit = Liters; Imperial conversion = Gallons), Powder—Prentox Prenfish Rotenone Fish Toxicant Powder (Kilograms; Imperial conversion= Pounds). [c] SS—Coho salmon *O. kistutch*, RT—Rainbow trout *O. mykiss*, GR–Arctic grayling *Thymallus arcticus*, AC—Arctic char *Salvelinus alpinus*, DV-Dolly Varden *Salvelinus malma*, LS—Longnose suckers *Catastomus catastomus*, SC—Sculpin spp. *Cottus spp*, ST—Threespine stickleback *Gasterosteus aculeatus*; Wild fish in Bold, otherwise hatchery stock. [d] Planned Treatments for October 2020.

In another project, the entire Soldotna Creek tributary drainage of the Kenai River was treated over the course of four years to prevent pike from dispersing into the Kenai River and establishing in more vulnerable tributary systems like the Moose River. This project included the treatment of seven lakes, over 32 km of flowing waters, and over 200 hectares of wetlands. The drainage was divided into two sections with temporary fish barriers (Figures 4 and 9). The first section included five lakes and connecting streams. These lakes no longer contained wild native game fish and were treated in 2014 except for a closed lake (Loon Lake) that was treated in 2017 immediately after pike were discovered (Table 1). In 2015, native fish from Soldotna Creek and Sevena Lake at the headwaters were intensively trapped and relocated into the then fishless four open lakes that had previously been treated (Table 2). In 2016 Sevena Lake and Soldotna Creek were treated, and Sevena Lake was precautionarily re-treated in 2017 because of the complexity of that area. The native fish relocations seeded fish populations in the drainage lakes, and Soldotna Creek was recolonized within 12 months by all previously occurring species via migration from the Kenai River [87].

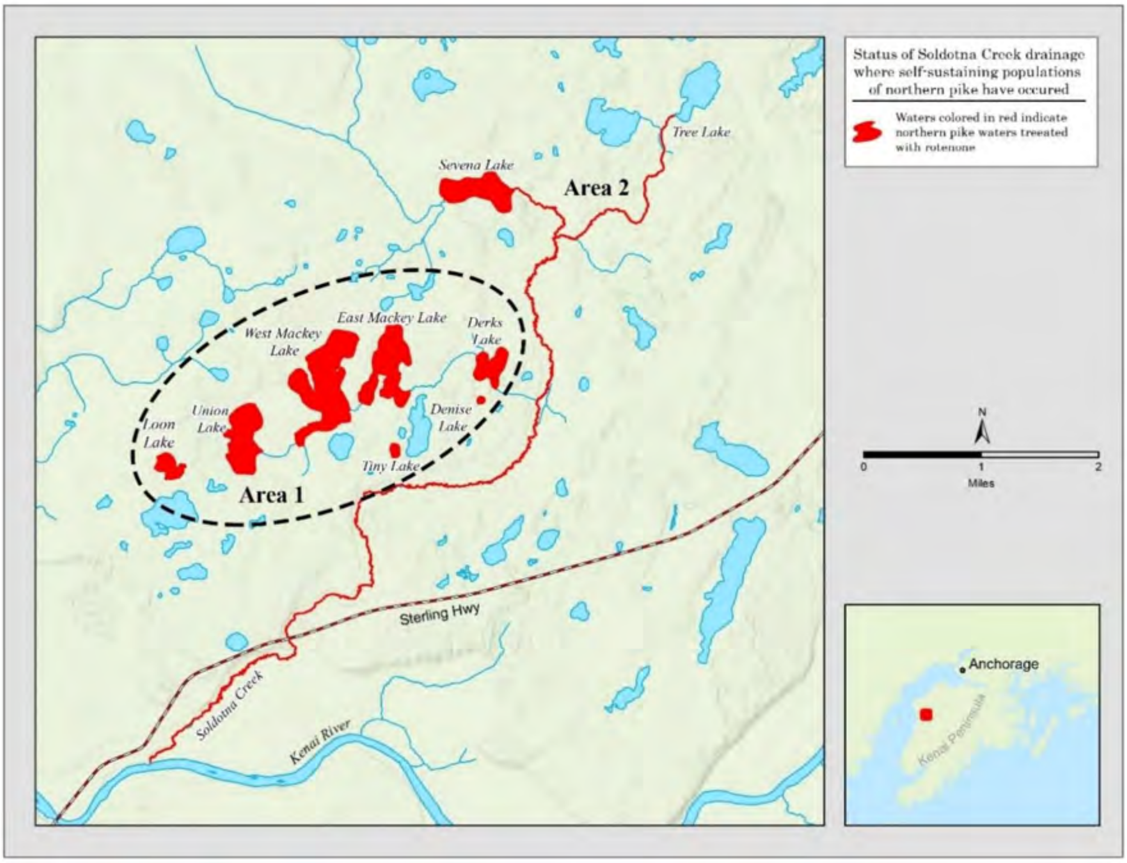

Figure 9. Map of the Soldotna Creek project area for the largest pike eradication project in SC Alaska. This eradication effort was completed between 2014 and 2018. Temporary barriers were installed to separate Area 1 (encircled) from Area 2 (Sevena Lake and Soldotna Creek). The lakes in Area 1 were treated in 2014 (Loon Lake was treated in 2017). During 2015, native fish from Area 2 were rescued and replanted in Area 1. Area 2 was treated in 2016 and 2017, and the barriers were removed to allow fish movement throughout the system.

Table 2. Native fish released into Soldotna Creek Pike Eradication Area 1 lakes during 2015–2018.

Year	Lake	Rainbow Trout [a]	Dolly Varden [b]	Threespine Stickleback [c]	Sculpin Spp. [d]	Coho Salmon [e]	All Species	Salmonids/Hectare [f,g]
2015	Derks	30	161	950	3	6107	7251	68
2016		199	217	3386	229	2452	6483	31
2017		0	0	0	0	38	38	1
	Total	229	378	4,336	232	8597	13,772	100
2015	East Mackey	355	366	5362	960	1396	8439	8
2016		696	484	4103	439	6564	12,286	31
2017		176	436	0	0	2506	3118	13
2018		220	436	0	0	2506	3162	13
	Total	1447	1722	9465	1399	12,972	27,005	65
2015	Union	195	173	3532	183	2173	6256	12
2016		277	407	3563	419	7259	11,925	38
2017		38	130	0	0	604	772	4
2018		35	0	0	0	0	35	1
	Total	545	710	7095	602	10,036	18,988	55
2015	West Mackey	354	437	5553	399	904	7647	4
2016		1088	1034	6401	1062	13,388	22,973	34
2017		203	556	0	0	3374	4,133	9
2018		679	0	0	0	0	679	2
	Total	2324	2027	11,954	1461	17,666	35,432	49
	Grand Total	4545	4837	32,850	3694	49,271	95,197	269

[a] Oncorhychus mykiss, [b] Salvelinus malma [c] Gasterosteus aculeatus,[d] Cottus spp., [e] Oncorhychus kisutch, [f] Juvenile salmonids were collected from the mainstem of Soldotna Creek and stickleback were collected mainly from Sevena Lake. [g] The majority of fish were collected by minnow trapping; other collection gear used included backpack electrofishing and fyke net traps.

An issue with rotenone projects that is often contentious with the public is concern for piscivorous waterfowl. While these animals are not affected directly by the piscicide, loss of fish prey can displace their populations. As general practice, rotenone projects for pike in SC Alaska now include relocations of sticklebacks in all cases where there are historic records of sticklebacks occurring. This provides a forage base for piscivorous birds and other wildlife in the lakes. It also provides a unique opportunity for evolutionary ecologists to study local adaptations of sticklebacks re-introduced to these lakes [10,96–98]. In several cases, these researchers have been substantial partners in the stickleback translocations.

Since 2008, rotenone treatments for pike eradications predominantly took place in Anchorage and the Kenai Peninsula. Both regions had feasible potential to eradicate invasive pike populations entirely if pike did not spread far beyond their distribution. This was in contrast to the highly interconnected and expansive range of pike in the Susitna Basin. Over the last decade, the primary focus of pike eradication efforts in SC Alaska has been working toward the achievement of this goal, which is uncommon in invasive species management [99]. At the time of writing of this review, both the Anchorage and Kenai Peninsula regions each have one known remaining lake system containing pike populations, and plans are in development for their eradications. If successful, both regions have great potential to eventually be free of invasive northern pike. With this milestone in reach, pike eradication efforts will begin north of Anchorage in two Knik Arm Drainage lakes in 2020 (Table 1, Figure 4).

3.3. Outreach and Angler Engagement

Outreach and angler engagement are interwoven into all pike suppression and eradication efforts and are a critical component of invasive pike management. Communication plans, websites, print materials, magazine articles, social media, media stories, presentations and seminars are all outreach tactics that are commonly used to disseminate information about pike in SC Alaska. For illegal introductions of pike or any other non-indigenous species to cease, public understanding of the ramifications of such actions must be well understood and translate to behavior change. While public opinion on pike in SC Alaska still varies greatly, there is a high degree of public support for invasive pike removals as well as a reluctant understanding that despite being a prized game species, pike in SC Alaska are invasive and must be managed as such. Anglers and the public are encouraged to report any new observations of pike or any other non-native species to a centralized reporting application (http://www.adfg.alaska.gov/index.cfm?adfg=invasivespeciesreporter.main) or by calling a statewide invasive species hotline (1-877-INVASIV). For records of where pike are known to occur, a database and interactive mapping tool for known pike waters is maintained (https://adfg.maps.arcgis.com/apps/webappviewer/index.html?id=ad27ebc052814b66a60d0e52701e64f7&_ga=2.40269538.1172137975.1582067549-1889826575.1579740028).

SC Alaska has some of the most liberalized sport fishing regulations for pike in the country. There is no bag or possession limit for them outside of their native range in the state. Anglers are allowed use of up to five lines while ice fishing, and methods and means not permissible for other species such as bow and arrow and spear can be used for pike. As of 2020, a regulation went into effect requiring anglers to dispatch any pike they catch in waters of the Susitna Basin, Knik Arm, Anchorage, or the Kenai Peninsula. Partnering with anglers to reduce pike abundance through harvest is a strategy that has the potential to both reduce abundance [22,100,101] and provide a means of acquiring observational data on pike in remote locations that are difficult and costly to access.

While bounties are an angler engagement tool implemented in other states [102], to date traditional bounties have not been employed as a pike management strategy in SC Alaska due to funding, complexities of proving the origin of the fish (i.e., native or invasive range), and most importantly, reluctance to create an economic incentive that could motivate additional illegal introductions. However, beginning in 2020, a new winter only ADFG angler incentive program was initiated in Alexander Lake where it was previously noted that pike suppression may now be warranted. Approximately 100 pike in this lake were tagged with passive integrated responder tags (PIT tags) during the summer of 2019. These tags were not visible to anglers. Anglers were encouraged to harvest pike in Alexander

Lake during the winter and bring them into the local ADFG office to be scanned. If an angler had a tag, they received a reward in the form of a $100 gift card and were entered into a drawing for a larger prize at the end of the season. During this first year of the program, approximately 500 pike were harvested, and 13 tags were recovered. This program provided a low-cost avenue for collecting baseline catch and effort data on pike in Alexander Lake, acquiring cleithra and otoliths from the fish for aging and microchemistry research, and facilitated communication and partnership with pike anglers. In addition, Alexander Creek pike suppression crews will be able to scan for tagged pike downstream during annual suppression to continue observing movement patterns of pike in that system. Because eligibility for an award was based on the chance of catching a tagged pike from a known location, there was no motivation for anyone to move pike a result of this program. In the future, this program may be expanded to other pike waters in SC Alaska.

3.4. Population Monitoring and Research

The final tenant of invasive pike management in SC Alaska involves monitoring of pike populations throughout the region and conducting research to learn more about the impacts of pike and effective management tools. Research on pike has been on-going over the last decade and, as has been discussed throughout this review, has included investigations into pike diets and impacts [12,16,50] movement patterns [44,45], population genetics [35], predicting invasion risk [35], developing eDNA tools for pike [92,93,103], and better understanding the degradation process of rotenone [UAA Unpublished]. All these investigations are highly collaborative among ADFG, the University of Alaska, the U.S. Geological Survey, and the U.S. Fish and Wildlife Service as well as local NGOs like the National Fish Habitat Partnerships (NFHP), Kenai Watershed Forum (KWF), CIAA, TTCD, and NVT. Future research will seek to expand alliances with commercial fisherman to acquire samples of pike caught in estuarine waters for otolith microchemistry investigations to learn how pike may be utilizing Cook Inlet for their current dispersal and to develop barrier designs to protect vulnerable drainages from that occurrence. Research will continue to evaluate effectiveness of current pike suppression efforts and look toward the future to determine what new tools and technologies might emerge, such as those in the genetics realm [104–107], that may have future applications for adaptive pike management in SC Alaska.

4. Conclusions

In conclusion, invasive northern pike in SC Alaska have had complex, and in many cases, severe consequences for native fish populations. Pike are certainly not the only factor responsible for salmon declines in the state, but in some cases, they are a substantial part of that story. In an age of climate change and deteriorating ecological conditions, progressive action to reduce stressors facing salmon and other native fish species in Alaska's freshwaters is imperative. Alaska is fortunate to not suffer many of the invasive species impacts that are rampant elsewhere, but there is no guarantee that good fortune will continue. As has been well documented with pike, invasive species are a threat to Alaska's fragile salmon habitats, and pike in SC is one factor that can be mitigated with effective and well prioritized adaptive management.

In this past decade of invasive pike management, significant strides were made toward pike eradication on the Kenai Peninsula and the Anchorage areas. Thousands of pike have been removed from large drainages in the Susitna Basin resulting in increased survival of rearing salmon. Over the last decade close to $5 Million has been spent on these efforts, but the economic value of fisheries in the state is far greater and the cultural value is immeasurable. The invasion and subsequent control efforts for pike in SC Alaska are the most spatially expansive in the world for this species making both the problem and the collaborative program to address it unique. However, there are other locations with similar challenges with invasive populations of pike. Among the most significant examples in the western Unites States are the eastern Columbia River Basin in Washington State and the Yampa River in Utah and Colorado. Significant efforts are underway in these locations to protect native species from pike predation and prevent pike from expanding their ranges. In the Columbia River, this is particularly important as downstream expansion of pike is anticipated to affect anadromous salmon populations just as they have in SC Alaska. In this regard, there is great benefit for western states with invasive pike challenges to collaborate so that successful methods and technologies can be broadly applied. Over the last decade, Alaska's invasive pike program has contributed to a greater understanding of predation impacts on salmonids and other native fish, helped develop enhanced detection capabilities (i.e., eDNA), pioneered largescale pike suppression (i.e., Alexander Creek), and completed over 20 successful eradications of invasive pike populations.

Moving forward, in this next decade of invasive pike management in SC Alaska, the goal will be to complete pike eradication on the Kenai Peninsula and in Anchorage, develop effective strategies and barriers to prevent future introductions, focus eradication efforts in northern Cook Inlet drainage waters where feasible, implement a standardized monitoring program for pike waters in the Susitna basin and use those data to develop effective strategies for continued pike suppression in the region. Ultimately, the primary objective in this coming decade, as it was in the last, will be to prevent pike from spreading beyond their current distribution and causing further damage to Alaska's fisheries.

Author Contributions: Conceptualization, K.D., R.M., P.B., C.J. ,N.S., A.W. and R.D; methodology, K.D, R.M., P.B., C.J., N.S., A.W, and R.D; formal analysis R.M., P.B., R.B; investigation K.D., R.M., P.B., C.J, N.S., A.W., R.D; resources K.D., P.B., C.J., R.M., N.S., A.W. R.D.; writing—original draft preparation K.D; writing—review and editing R.M., P.B., C.J., N.S., A.W. and R.D.; visualization K.D., R.M. N.S.; supervision K.D.,R.M., P.B., N.S., A.W., R.D.; project administration K.D., N.S., R.D.; funding acquisition K.D., N.S., R.D. All authors have read and agreed to the published version of the manuscript.

Funding: Projects discussed in this manuscript were funded by a variety of sources, primarily the Alaska Sustainable Salmon Fund (Grant #s 44609, 44613, 44617,44626, 44807, 44910, 44168, 44353, 44365, 51003, 52013), the Aquatic Nuisance Species Task Force (701818G496), Joint-Base Elmendorf Richardson (COOP 14-010), Matanuska-Susitna Borough (2016-00002088, 2016-00002091), U.S. Fish and Wildlife Service (FWS70181AJ), the Bureau of Indian Affairs (A18AV00629), and State Wildlife Grants (T-10-12).

Acknowledgments: The authors wish to offer their sincere gratitude to Adam Sepulveda with the U.S. Geological Survey Rocky Mountain Science Center. Sepulveda has been a mentor to all authors and a critical partner and collaborator on invasive pike research in SC Alaska. The authors also wish to thank Peter Westley, Andres Lopez, Jeffrey Falke, Matthew Wooller, and Patrick Tomco with the University of Alaska for continued collaboration. Special thanks to Chase Jalbert for this graduate research on pike genetics patterns and invasion potential in SC Alaska. Tammy Davis is the statewide Invasive Species Coordinator for the state of Alaska and is an integral member of the team and a constant support for invasive pike efforts in SC Alaska. Also, the authors sincerely thank David Rutz, ADFG Sport Fish Division Director, for his passionate support of invasive pike efforts and tremendous field assistance. Progress made with invasive pike suppression and eradication in SC Alaska would not be possible without the substantial field and management contributions by the following individuals: Timothy McKinley, Tom Vania, Matt Miller, James Hasbrouck, Jack Erickson, Robert Begich, Colton Lipka, Samantha Oslund, Samuel Ivey, Jerry Strait, Eric Hollerbach, Jillian Jablonski, Christy Cincotta, Justin Trenton, Jessica Johnson, Emily Heale, Savanna Van Diest, Gerrit Van Diest, Tyler Henegan, Kristopher Butler, Cole Deal, RJ Lister, Jordan Couture, Chris Razink, Adrian Baer, Keegun Egelus, Chuck Brazil, Bob Pence, Rip Bliss, and Anne Bliss. Biometric assistance was provided by Ben Buzzee and Adam Craig, and GIS assistance by Skip Repetto and Jason Graham. Most of all, the authors thank their supportive family and friends who endure their frequent absences so the work of protecting Alaska's native fish from invasive pike can be accomplished.

Conflicts of Interest: The authors declare no conflict of interest. Funders of the projects discussed had no role in project design; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Table A1. ADFG Sport Fish Division Invasive Northern Pike Project Prioritization Matrix.

Questions/Criteria	Priority Level (Low, Medium, High)	Weighted** Score	Enter 1 or 0 (Yes = 1) (No = 0)	Score Value
Recreational Fisheries				
Pre-pike introduction, historic fishing level in the water body was low (≤200 days)	Low	1		0
Pre-pike introduction, historic fishing level in the water body was medium (>200–≤1000 days)	Medium	5		0
Pre-pike introduction, historic fishing level in the water body was high (>1000 days)	High	10		0
Is a goal of the project to r restore opportunity for a non-pike fishery?	Medium	5		0
Is the water body currently and/ or formerly stocked by ADFG?	Medium	5		0
Have stocking levels in the water body been altered because of pike presence?	Medium	5		0
Pike Impacts				
Do pike in the water body directly threaten a wild fishery in that water?	High	10		0
Do pike in the water body threaten a wild fishery that is in close proximity (five miles or less)?	High	10		0
Have regulations for wild sport fisheries exceeding 1000 angler-days been restricted because of pike in this waterbody?	High	10		0
Have wild sport fisheries receiving under 1000 angler-days of effort been restricted because of pike in this waterbody?	Low	1		0
Have available data indicated that a wild fish population has been eliminated associated with pike presence?	High	10		0
Have available data indicated that a wild fish population has been impacted associated with pike presence?	Medium	5		0
Has the public indicated concern over the pike population in this water body?	Medium	5		0
Do pike represent >50% of the catch in a netting survey or from other available data?	High	10		0
Do pike represent 25–50% of the catch in a netting survey or from other available data?	Medium	5		0
Do pike represent <25% of the catch in a netting survey or from other available data?	Low	1		0
Does the area management biologist expect a negative impact to a sport fishery associated with pike in this waterbody?	High	10		0
Does the area management biologist expect an imminent loss of a wild stock associated with pike in this drainage?	Very High	30		0
Does the area management biologist associate pike with an inability to meet an escapement goal in this drainage?	High	10		0
Does this water body contain a Board of Fisheries-stock of yield or management concern?	High	10		0
Eliminating pike in this project area removes the pike threat in the entire management area	Very High	30		0
Education and Outreach				
Are there opportunities to use this project as an educational outreach tool to increase public awareness?	High	10		0
Are we demonstrating a pike control strategy to stakeholders?	Medium	5		0
Does the project foster public understanding and awareness of invasive species	Medium	5		0
Has there already been stakeholder input desiring a project of this nature?	High	10		0
Habitat Significance				
Is the project area within an open system?	High	10		0
If successful, can this project prevent pike distribution throughout the drainage?	Very High	30		0
Is the project area within an anadromous system?	High	10		0
Are wild, resident fish species present?	Medium	5		0
If in a closed system, does the project have the potential to reduce native fish populations?	Medium	−5		0
Is the project designed to improve habitat for threatened or endangered species populations?	High	10		0
Project Area Characterization (*Type 1—Suitable pike habitat*, *Type 2—Marginally suitable habitat*, *Type 3—Poor pike habitat*)				

Table A1. *Cont.*

Questions/Criteria	Priority Level (Low, Medium, High)	Weighted** Score	Enter 1 or 0 (Yes = 1) (No = 0)	Score Value
(Lakes/Wetlands)				
Is it a Type 1 Lake or wetland—Eutrophic and primarily shallow (≤15 feet) with abundant vegetation throughout?	High	10		0
Is it a Type 2 Lake—Mesotrophic and primarily deep (>15 feet) with vegetation covering 50% or more of the lake?	Medium	5		0
Is it a Type 3 Lake—Oligotrophic and primarily deep (>15 feet) with wither sparse or no aquatic vegetation)?	Low	1		0
(Rivers and Streams)*				
Is the waterbody primarily Type 1—Low stream slope (0.0–0.5%) with abundant vegetation and is capable of supporting rearing coho (i.e., Moose River, Alexander River)?	High	10		0
Is the waterbody primarily Type 2 with some type 1—Moderate stream slope (0.51–2.0%) with semi-permanent woody debris and back-waters sloughs and is capable of supporting rearing coho (i.e., Deshka River)?	Medium	5		0
Is the waterbody primarily Type 2—Moderate stream slope (0.51–2.0%) with semi-permanent woody debris and is capable of supporting rearing coho (i.e., Campbell Creek)?	Medium	5		0
Is the waterbody a combination of Types 2 & 3—High stream slope (>2.0%) and slow back-water sloughs capable of supporting rearing coho (i.e., Willow Creek?)	Medium	5		0
Is the waterbody primarily Type 3—Clear, high stream slope (>2.0%) with few slower back-waters (i.e., the Little Susitna River)?	Low	1		0
Is the waterbody exclusively Type 3—High stream slope (>2.0%) with extensive glacial turbidity (i.e., Klutina River)?	Low	1		0
Cultural Significance				
Are native cultural activities (i.e., fish camps, etc.) threatened by pike in this water body?	High	10		0
Does the project benefit subsistence fisheries?	High	10		0
Is a goal of the project to provide economic benefits for citizens, communities, or industries?	High	10		0
Does the area manager believe that user groups are negatively affected by the pike presence?	High	10		0
Economic Impacts				
Has the area manager received input from local businesses/property owners that they are experiencing a negative financial effect from pike in this water body?	High	10		0
Does the project protect commercially important species?	High	10		0
Research				
Will project goals, objectives, and tasks within the project plan strive to improve understanding of pike behavior or distribution in local waters?	Medium	5		0
Do project goals strive to improve understanding of control or eradication techniques for pike?	High	10		0
Will the project include a follow-up assessment to measure the effects of the management action?	Medium	5		0
Do project goals strive to quantify fishery/economic losses resulting from invasive pike?	Medium	5		0
Feasibility				
Does the water body have public access?	High	10		0
Is the water body on the road system?	Low	1		0
Is it technically feasible that the pike population could be permanently removed or contained if the project is implemented?	High	10		0
Is there a history of reintroductions of pike in this area?	High	−10		0
Is the project designed to achieve program goals within the funding period?	Low	1		0
Does the project achieve long term program goals within a decade of the funding period? (i.e., reestablish wild fish populations)	High	10		0
Can the project begin when funding is received?	Medium	5		0
The goal of the project is to have a measurable, positive outcome for fisheries.	High	10		0

Table A1. *Cont.*

Questions/Criteria	Priority Level (Low, Medium, High)	Weighted** Score	Enter 1 or 0 (Yes = 1) (No = 0)	Score Value
Permitting and Inter-Agency Cooperation				
Does the project provide opportunities to partner or collaborate with other agencies or organizations?	Low	1		0
Is the NEPA process required for this project?	Low	−1		0
Is there reason to believe there would be a conflict with an existing coastal, watershed or restoration plan?	High	−10		0
ADFG Significance				
Is the project programmatically/ scientifically aligned with ADF&G's mission in the Sport Fish Division Strategic Plan?	High	10		0
SCORE				

*** Rearing Coho share the same habitat requirements as northern pike (Rutz 2006) and are a good indicator of pike habitat suitability and potential overlap. ** Low = 1, Medium = 5, High = 10. Note: If project includes work in both categories, score both. Otherwise, score one or the other only.

References

1. Havel, J.E.; Kovalenko, K.E.; Thmoaz, S.M.; Amalifitano, S.; Kats, L.B. Aquatic invasive species: Challenges for the future. *Hydrobiologia* **2015**, *750*, 147–170. [CrossRef] [PubMed]
2. Britton, J.R.; Gozlan, R.W.; Copp, G.H. Managing non-native fish in the environment. *Fish Fish.* **2011**, *12*, 256–274. [CrossRef]
3. Ricciardi, A.; Hoopes, M.F.; Marchetti, M.P.; Lockwood, J.L. Progress toward understanding the ecological implacts of non-native species. *Ecol. Monogr.* **2013**, *8*, 263–282. [CrossRef]
4. Simberloff, D. Invasive species. In *Conservation Biology for All*; Sodhi, N.S., Ehrich, S.R., Eds.; Oxford University Press: New York, NY, USA, 2007.
5. Dunker, K.J.; Sepulveda, A.; Massengill, R.; Rutz, D. The northern pike, a prized native but disastrous invasive. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 356–398.
6. Lever, C. *Naturalized Fishes of the World*; Academic Press: San Diego, CA, USA, 1996.
7. Welcomme, R.L. *International Introductions of Inland Aquatic Species*; TP No. 294; Food and Agriculture Organization of the United Nations: Rome, Italy, 1988; pp. 112–113.
8. Inskip, P.D. *Habitat Suitability Index Models: Northern Pike*; FWS/OBS 82/10.17; United States Fish and Wildlife Service: Daphne, AL, USA, 1982.
9. Persson, A.P.A.N.; Brönmark, C. Trophic interactions. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 185–211.
10. Heins, D.C.; Knoper, H.; Baker, J.A. Consumptive and non-consumptive effects of predation by introduced northern pike on life history traits in threespine stickleback. *Evol. Ecol. Res.* **2016**, *17*, 355–372.
11. Byström, P.; Karlsson, J.; Nilsson, P.A.; Van Kooten, T.; Ask, J.; Olofsson, F. Substitution of top predators:effects of pike invasion in a subarctic lake. *Freshw. Biol.* **2007**, *52*, 1271–1280. [CrossRef]
12. Sepulveda, A.J.; Rutz, D.S.; Dupuis, A.W.; Shields, P.A.; Dunker, K.J. Introduced northern pike consumption of salmonids in Southcentral Alaska. *Ecol. Freshw. Fish* **2014**. [CrossRef]
13. McKinley, T. *Survey of Northern Pike in Lakes of Soldotna Creek Drainage, 2002*; Special Publication No. 13-02; Alaska Department of Fish and Game: Anchorage, AK, USA, 2013.
14. Beck, K.G.; Zimmerman, K.; Schardt, J.D.; Stone, J.; Lukens, R.R.; Reichard, S.; Randall, J.; Cangelosi, A.A.; Cooper, D.; Thompson, J.P. Invasive species defined in a policy context: Recommendations from the federal invasive species advisory committee. *Invasive Plant Sci. Manag.* **2008**, *1*, 414–421. [CrossRef]
15. Nilsson, P.A.; Eklöv, P. Finding food and staying alive. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 9–31.
16. Sepulveda, A.J.; Rutz, D.S.; Ivey, S.S.; Dunker, K.J.; Gross, J.A. Introduced northern pike predation on salmonids in Southcentral Alaska. *Ecol. Freshw. Fish* **2013**. [CrossRef]
17. Jacobsen, L.; Engström-Öst, J. Coping with environments; vegetation, turbidity and abiotics. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 32–61.
18. Craig, J.F. *Pike: Biology and Exploitation*; Chapman & Hall: London, UK, 1996.
19. Raat, A.J.P. *Synopsis of Biological Data on the Northern Pike Esox Lucius Linneaeus, 1758*; FAO Fisheries Synopsis No. 30 Rev. 2; Food and Agriculture Organization of the United Nations: Rome, Italy, 1988.
20. Haugen, T.O.; Vøllestad, L.A. Pike population size and structure: Influence of density-dependent and density-independent factors. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 123–163.
21. Mann, R.H.K. The numbers and production of pike (*Esox lucius*) in two Dorset rivers. *J. Anim. Ecol.* **1980**, *49*, 899–915. [CrossRef]
22. Arlinghaus, R.J.A.; Beardmore, B.; Diaz, A.M.; Hühn, D.; Johnston, F.; Klefoth, T.; Kuparinen, A.; Matsumura, S.; Pagel, T.; Pieterek, T.; et al. Recreational piking—Sustainably managing pike in recreational fisheries. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 288–336.
23. Kuparinen, A.H.L. Northern pike commercial fisheries, stock assessment and aquaculture. In *Biology and Ecology of Pike*; Skov, C., Nilsson, P.A., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 337–355.
24. McMahon, T.E.; Bennet, D.H. Walleye and northern pike: Boost or bane to northwest fisheries. *Fisheries* **1996**, *21*, 6–13. [CrossRef]

25. Zelasko, K.A.; Bestgen, K.R.; Hawkins, J.A.; White, G.C. Evaluation of a long-term predator removal program: Abundance and population synamics of invasive northern pike in the Yampa River, Colorado. *Trans. Am. Fish. Soc.* **2016**, *145*, 1153–1170. [CrossRef]
26. Harvey, S.; Bean, N. *Non-Native Fish Suppression Project, May 2018–April 2019 Annual Report*; Project Number 2007-149-00; Kalispel Tribe of Indians: Usk, WA, USA, 2019; p. 68.
27. Walrath, J.D.; Quist, M.C.; Firehammer, J.A. Trophic ecology of nonnative northern pike and thier effect on conservation of native westslope cutthroat trout. *N. Am. J. Fish. Manag.* **2015**, *35*, 158–177. [CrossRef]
28. Muhlfeld, C.C.; Bennett, D.H.; Steinhorst, R.K.; Marotz, B.; Boyer, M. Using bioenergetics modeling to estiamte consumption of native juvenile salmonids by nonnative northern pike in the Upper Flathead River system, Montana. *N. Am. J. Fish. Manag.* **2008**, *28*, 636–648. [CrossRef]
29. Mecklenburg, C.W.; Mecklenburg, T.A.; Thorsteinson, L.K. *Fishes of Alaska*; American Fisheries Society: Bethesda, MD, USA, 2002; p. 1037.
30. Morrow, J.E. *The Freshwater Fishes of Alaska*; Northwest Publishing Company: Anchorage, AK, USA, 1980; p. 248.
31. Oswood, M.W.; Reynolds, J.B.; Irons, J.G., III; Milner, A.M. Distributions of freshwater fishes in ecoregions and hydroregions of Alaska. *J. N. Am. Benthol. Soc.* **2000**, *19*, 405–418. [CrossRef]
32. Seeb, J.E.; Seeb, L.W.; Oates, D.W.; Utter, F.M. Genetic nvariation and postglacial dispersal of populations of northern pike (*Esox lucius*) in North America. *Can. J. Fish. Aquat. Sci.* **1986**, *44*, 556–561. [CrossRef]
33. Haught, S.; von Hippel, F.A. Invasive pike establishment in Cook Inlet Basin lakes, Alaska: Diet, native fish abundance and lake environment. *Biol. Invasions* **2011**, *13*, 2103–2114. [CrossRef]
34. Patankar, R.; von Hippel, F.A.; Bell, M.A. Extinction of a weakly armoured threespine stickleback (Gasterosteus aculteatus) population in Prator Lake, Alaska. *Ecol. Freshw. Fish* **2006**, *15*, 482–487. [CrossRef]
35. Jalbert, C.S. Impacts of a Top Predator (Esox lucius) on Salmonids in Southcentral Alaska: Genetics, Connectivity, and Vulnerability. Master's Thesis, University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, Fairbanks, AK, USA, 2018.
36. Spens, J.; Ball, J.P. Salmonid or nonsalmonid lakes: Predicting the fate of northern boreal fish communities with hierarchical filters relating to a keystone piscivore. *Can. J. Fish. Aquat. Sci.* **2008**, *65*, 1945–1955. [CrossRef]
37. Baker, B. *Fishery Management Report for Recreational Fishereies in the Tanana River Management Area, 2017, Alaska*; Fishery Management Report No. 18-33; Alaska Department of Fish and Game: Anchorage, AK, USA, 2018; p. 92.
38. Stuby, L. *Fishery Management Report for Sport Fisheries in the Yukon Management Area, 2017, Alaska*; Fishery Management Report No. 18-30; Alaska Department of Fish and Game: Anchorage, AK, USA, 2018; p. 62.
39. Rutz, D.S. *Movements, Food Availability and Stomach Contents of Northern Pike Selected Susitna River Drainages, 1996–1997.*; Fishery Data Series No. 99-5; Alaska Department of Fish and Game: Anchorage, AK, USA, 1999; p. 78.
40. Rutz, D.S. *Seasonal Movements, Age, and Size Statistics, and Food Habits of Upper Cook Inlet Northern Pike during 1994 and 1995*; Fishery Data Series No. 96-29; Alaska Department of Fish and Game: Anchorage, AK, USA, 1996; p. 65.
41. Glick, W.J.; Willette, T.M. *Relative Abundance, Food Habits, Age, and Growth of Northern Pike in 5 Susitna River Drainage Lakes, 2009–2012*; Fishery Data Series No. 16-34; Alaska Department of Fish and Game: Anchorage, AK, USA, 2016; p. 55.
42. Eklöv, P.; Hamrin, S.F. Predatory efficiency and prey selection: Interactions between pike, *Esox lucius*, perch *Perca fluvialtilis* and rudd *Scardinus erythrophthalmus*. *Oikos* **1989**, *56*, 149–156. [CrossRef]
43. Rutz, D.S.; Bradley, P.T.; Jacobson, C.; Dunker, K.J. *Alexander Creek Northern Pike Suppression, 2011–2018, Alaska*; Fishery Data Series No. 20-17; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; p. 34.
44. Rutz, D.S.; Dunker, K.J.; Bradley, P.T.; Jacobson, C. *Movement Patters of Northern Pike in Alexander Lake*; Fishery Data Series No. 20-16; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; p. 50.
45. Massengill, R. *Stormy Lake Northern Pike Distribution and Movement Study to Inform Future Eradication Efforts*; Special Publication No. 17-17; Alaska Department of Fish and Game: Anchorage, AK, USA, 2017; p. 58.
46. Mills, M.J. *Alaska Statewide Sport Fish Harvest Studies*; Federal Aid in Fish Restoration, Annual Performance Report 1985–1986, Project F-10-1(27) RT-2; Alaska Department of Fish and Game: Juneau, AK, USA, 1986.
47. Oslund, S.; Ivey, S.; Lescanec, D. *Area Management Report for the Sport Fishereis of Northern Cook Inlet, 2017–2018*; Fishery Management Report No. 20-04; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; p. 322.
48. ADFG Chinook Salmon Research Team. *Chinook Salmon Assessment and Research Plan*; Special Publication No. 13-01; Alaska Department of Fish and Game: Anchorage, AK, USA, 2013; p. 62.

49. Romberg, W.J.; Raffety, I.; Martz, M. *Estimates of Participation, Catch, and Havest in Alaska Sport Fisheries*; Fishery Data Series No. In Prep; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; in prep.
50. Catchcart, C.N.; Dunker, K.J.; Quinn, T.P.; Sepulveda, A.J.; von Hippel, F.A.; Wizik, A.; Young, D.B.; Westley, P.A.H. Trophic plasticity and the invasion of a renowned piscivore: A diet synthesis of northern pike (*Esox lucius*) from the native and introduced ranges in Alaska, U.S.A. *Biol. Invasions* **2019**, *21*, 1379–1392. [CrossRef]
51. Chihuly, M.B. Biology of the Northern Pike, *Esox lucius* Linneaus, in the Wood Lakes System of Alaska, with Emphasis on Lake Alegnagik. Master's Thesis, University of Alaska Fairbanks, College of Environmental Sciences, Fairbanks, AK, USA, 1979.
52. Dye, J.; Wallendorf, M.; Naughton, G.P.; Gryska, A.D. *Stock Assessment of Northern Pike in Lake Aleknagik, 1998–1999*; Fishery Data Series No. 02-14; Alaska Department of Fish and Game: Anchorage, AK, USA, 2002; p. 18.
53. Wuttig, K.G. *Estimated Abundance of Northern Pike in Harding Lake, 2012*; Fishery Data Series No. 15-39; Alaska Department of Fish and Game: Anchorage, AK, USA, 2012; p. 32.
54. Russell, R. *A Fisheries Inventory of Waters in the Lake Clark National Monument Area*; Alaska Department of Fish and Game: Anchorage, AK, USA, 1980; p. 207.
55. Schwanke, C.J. *Abundance, Length Composition, and Movement of the Northern Pike Populations in Long Lake of the Chulitna River Dainage, 2007–2010*; Fishery Data Sereies No. 12-23; Alaska Department of Fish and Game: Anchorage, AK, USA, 2012; p. 32.
56. Massengill, R. *Control Efforts for Invasive Northern Pike on the Kenai Peninsula, 2005–2006*; Fishery Data Series No. 10-05; Alaska Department of Fish and Game: Anchorage, AK, USA, 2010; p. 35.
57. Massengill, R. *Control Efforts for Invasive Northern Pike Esox lucius on the Kenai Peninsula, 2007*; Fishery Data Series No. 11-10; Alaska Department of Fish and Game: Anchorage, AK, USA, 2011; p. 49.
58. Massengill, R. *Control Efforts for Invasive Northern Pike on the Kenai Peninsula, 2009*; Special Publication No. 14-11; Alaska Department of Fish and Game: Anchorage, AK, USA, 2014; p. 84.
59. Massengill, R. *Control Efforts for Invasive Northern Pike on the Kenai Peninsula, 2008*; Special Publication No. 14-12; Alaska Department of Fish and Game: Anchorage, AK, USA, 2014; p. 74.
60. Massengill, R. *Stormy Lake Restoration: Invasive Northern Pike Eradication, 2012*; Special Publication No. 17-18; Alaska Department of Fish and Game: Anchorage, AK, USA, 2017; p. 98.
61. ADFG Southcentral Northern Pike Control Committee. *Management Plan for Invasive Northern Pike in Alaska*; Alaska Department of Fish and Game: Anchorage, AK, USA, 2007; p. 62.
62. Fay, V. *Alaska Aquatic Nuisance Species Management Plan*; Alaska Department of Fish and Gmae: Juneau, AK, USA, 2002; p. 116.
63. Syslo, J.M.; Guy, C.S.; Bigelow, P.E.; Doepke, P.D.; Ertel, B.D.; Koel, T.M. Response of non-native lake trout (*Salvelinus namaycush*) to 15 years of harvest in Yellowstone Lake, Yellowstone National Park. *Can. J. Fish. Aquat. Sci.* **2011**, *68*, 2132–2145. [CrossRef]
64. Syslo, J.M.; Guy, C.S.; Cox, B.S. Comparison of harvest scenarios for the cost-effective supression of lake trout in Swan Lake, Montana. *N. Am. J. Fish. Manag.* **2013**, *33*, 1079–1090. [CrossRef]
65. Cook Inlet Staff. *Alexander Creek King Salmon Stock Status and Action Plan, 2020*; Report to the Board of Fisheries; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; p. 29.
66. Bradley, P.; Jacobson, C.; Dunker, K. *Operational Plan: Alexander Creeknorthern Pike Suppression 2019–2021*; Regional Operational Plan ROF.SF.2A2019.04; Alaska Department of Fish and Game: Anchorage, AK, USA, 2019; p. 31.
67. King, B.E.; Walker, S.C. *Susitna River Sockeye Salmon Fry Studies, 1994 and 1995*; Alaska Department of Fish and Game: Anchorage, AK, USA, 1997; p. 58.
68. Courtney, M.B.; Schoen, E.R.; Wizik, A.; Westley, P.A.H. Quantifying the net benefits of suppression: Truncated size structure and consuption of native salmonids by invasive northern pike in an Alaska lake. *N. Am. J. Fish. Manag.* **2018**, *38*, 1306–1315. [CrossRef]
69. DeCino, R.; Willette, T.M. *Chelatna Lake Northern Pike Suppression Project 2017–2019*; Regional Operational Plan ROP.CF.4K2017.11; Alaska Department of Fish and Game: Soldotna, AK, USA, 2017; p. 22.
70. Tarbox, K.E.; Kyle, G.B. *An Estimate of Adult Sockeye Salmon (Oncorhynchus Nerka) Production, Based on Euphotic Volume, for the Susitna River Drainage, Alaska*; Alaska Department of Fish and Game: Anchorage, AK, USA, 1989; p. 59.

71. Wizik, A. *Shell Lake Sockeye Salmon Progress Report 2015*; Cook Inlet Aquaculture Association: Soldotna, AK, USA, 2015; p. 49.
72. Wizik, A.; Schoen, E.; Courtney, M.; Westley, P. *Shell Lake Sockeye Salmon Progress Report 2017*; Cook Inlet Aquaculture Association: Soldotna, AK, USA, 2017; p. 63.
73. Wizik, A. *Shell Lake Sockeye Salmon Progress Report 2018*; Cook Inlet Aquaculture Association: Soldotna, AK, USA, 2018; p. 59.
74. DeCino, R.; Willette, T.M. *Chelatna Lake Pike Suppression*; Fishery Data Series No. In Prep; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; in prep.
75. Yanusz, R.J.; Merizon, R.A.; Willette, T.M.; Evans, D.G.; Spencer, T.R.; Raborn, S. *Inriver Abundance and Spawning Distribution of Susitna River Sockeye Salmon Oncorhynchus Nerka, 2006*; Fishery Data Series 07-83; Alaska Department of Fish and Game: Anchorage, AK, USA, 2007; p. 68.
76. Yanusz, R.J.; Merizon, R.A.; Willette, T.M.; Evans, D.G.; Spencer, T.R. *Inriver Abundance and Istribution of Spawning Susitna River Sockeye Salmon Oncorhynchus Nerka, 2007*; Fishery Data Series No. 11-19; Alaska Department of Fish and Game: Anchorage, AK, USA, 2011; p. 50.
77. Yanusz, R.J.; Merizon, R.A.; Willette, T.M.; Evans, D.G.; Spencer, T.R. *Inriver Abundance and Spawning Distribution of Spawning Susitina River Sockeye Salmon Onchorhynchus Nerka, 2008*; Fishery Data Series No. 11-12; Alaska Department of Fish and Game: Anchorage, AK, USA, 2011; p. 44.
78. DeCino, R.; Willette, T.M. *Susitna River Drainage Lakes Pelagic Fish Estimates, Using Split-Beam Hydroacoustic and Midwater Trawl Sampling Techniques, 2005–2008*; Fishery Data Series No. 14-47; Alaska Department of Fish and Game: Anchorage, AK, USA, 2014; p. 58.
79. Smukall, M. *Whiskey Lake Salmon Smolt Progress Report, 2014*; Cook Inlet Aquaculture Association: Soldotna, AK, USA, 2015; p. 33.
80. Smukall, M. *Northern Pike Investigations Final Report (2012–2014)*; Cook Inlet Aquaculture Association: Soldotna, AK, USA, 2015; p. 69.
81. Dunker, K.; Bradley, P.; Jacobson, C. *Threemile Lake Invasive Northern Pike Population Assessment*; Regional Operational Plan SF.2A.2018.11; Alaska Department of Fish and Game: Anchorage, AK, USA, 2018; p. 38.
82. Bradley, P.; Jacobson, C.; Dunker, K. *Operational Plan: Threemile Lake Invasive Northern Pike Suppression and Chuitbuna Lake Population Assessment*; Regional Operational Plan SF.2A.2020.01; Alaska Department of Fish and Game: Anchorage, AK, USA, 2019; p. 28.
83. Larsson, P.; Tibblin, P.; Koch-Schmidt, P.; Engstedt, O.; Nilsson, J.; Nordahl, O.; Forsman, A. Ecology, evolution, and management strategies of northern pike populations in the Baltic Sea. *Ambio* **2015**, *44*, 451–461. [CrossRef] [PubMed]
84. Walther, B.D.; Limburg, K.E. The use of otolith chemistry to characterize diadrmous migrations. *J. Fish Biol.* **2012**, *81*, 796–825. [CrossRef]
85. Britton, J.R.; Brazier, M.; Davies, G.D.; Chare, S.I. Case studies on eradicating the Asiatic cyprinid Pseudorasbora parva from fishing lakes in England to prevent their riverine dispersal. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2008**, *18*, 867–876. [CrossRef]
86. Knapp, R.A.; Matthews, K.R. Eradication of nonnative fish by gillnetting from a small mountain lake in California. *Restor. Ecol.* **1998**, *6*, 207–213. [CrossRef]
87. Massengill, R. *Soldotna Creek Drainage Restoration: Invasive Northern Pike Eradication, 2014–2018*; Special Publication No. In Prep; Alaska Department of Fish and Game: Anchorage, AK, USA, 2020; in prep.
88. Finlayson, B.; Skaar, D.; Anderson, J.; Carter, J.; Duffield, D.; Flammang, M.; Jackson, C.; Overlock, J.; Steinkjer, J.; Wilson, R. *Planning and Standard Operating Procedures for the Use of Rotenone in Fish Management—Rotenone SOP Manual*, 2nd ed.; American Fisheries Society: Bethesda, MD, USA, 2018; p. 176.
89. USEPA. *Reregistration Eligibility Decision for Rotenone*; Document EPA 738-R-07-005; United States Environmental Protection Agency: Washington, DC, USA, 2007; p. 45.
90. Ling, N. *Rotenone—A Review of Its Toxicity and Use for Fisheries Management*; Science for Conservation 211; New Zealand Department of Conseration: Wellington, New Zealand, 2003; p. 40.
91. Dalu, T.; Wasserman, R.J.; Jordaan, M.; Froneman, W.P.; Wey, O.L.F. An assessment of the effect of rotenone on selected non-target aquatic fauna. *PLoS ONE* **2015**, *10*(11), e0142140. [CrossRef]
92. Dunker, K.J.; Sepulveda, A.J.; Massengill, R.L.; Olsen, J.B.; Russ, O.L.; Wenburg, J.K.; Antonovich, A. Potential of environmental DNA to evaluate northern pike (*Esox lucius*) eradication efforts: An experimental test and case study. *PLoS ONE* **2016**, *11*(9), e0162277. [CrossRef]

93. Sepulveda, A.J.; Hutchins, P.R.; Massengill, R.L.; Dunker, K.J. Tradeoffs of a portable, field-based environmental DNA platform for detecting invasive northern pike (*Esox lucius*) in Alaska. *Manag. Biol. Invasions* **2018**, *9*, 253–258. [CrossRef]
94. Massengill, R.; Begich, L.R.; Dunker, K. *Kenai Peninsula Invasive Northern Pike Monitoring and Native Fish Restoration*; Regional Operational Plan SF.2A.2020.02; Alaska Department of Fish and Game: Anchorage, AK, USA, 2018.
95. ADF&G. *Statewide Stocking Plan for Sport Fish, 2020–2024*; Alaska Deparment of Fish and Game: Anchorage, AK, USA, 2020; p. 26.
96. Bell, M.A.; Heins, D.C.; Wund, M.A.; von Hippel, F.A.; Massengill, R.; Dunker, K.; Bristow, G.A.; Aquirre, W.E. Reintroduction of threespine stickleback into Cheney and Scout Lakes, Alaska. *Evol. Ecol. Res.* **2016**, *17*, 157–178.
97. Wund, M.A.; Singh, O.D.; Geiselman, A.; Bell, M.A. Morphological evolution of an anadromous threespine stickleback population within one generation after reintroduction to Cheney Lake, Alaska. *Evol. Ecol. Res.* **2016**, *17*, 203–224.
98. Kurz, M.L.; Heins, D.C.; Bell, M.A.; von Hippel, F.A. Shifts in life-history traits of two introduced populations of threespine stickleback. *Evol. Ecol. Res.* **2016**, *17*, 225–242.
99. Parkes, J.P.; Panetta, F.D. Eradication of invasive species: Progress and emerging issues in the 21st century. In *Invasive Speces Management: A Handbook of Principles and Techniques*; Oxford University Press: Oxford, UK, 2009; pp. 44–72.
100. Post, J.R.; Sullivan, M.; Cox, S.; Lester, N.P.; Walters, C.J.; Parkinson, E.A.; Paul, A.J.; Jackson, J.; Shuter, B.J. Canada's recreational fishereis: The invisible collapse? *Fisheries* **2002**, *27*, 6–17. [CrossRef]
101. Pierce, R.B.; Tomcko, C.M.; Schupp, D.H. Exploitation of northern pike in seven small north-central Minnesota lakes. *N. Am. J. Fish. Manag.* **1995**, *15*, 601–609. [CrossRef]
102. Pansko, S.; Goldberg, J. Review of harvest incentives to control invasive species. *Manag. Biol. Invasions* **2014**, *5*, 263–277. [CrossRef]
103. Olsen, J.B.; Lewis, C.J.; Massengill, R.L.; Dunker, K.J.; Wenburg, J.K. An evaluation of target specificity and sensitivity of three qPCR assays for detecting environmental DNA from Northern Pike (*Esox lucius*). *Conserv. Genet. Resour.* **2015**. [CrossRef]
104. Schill, D.J.; Heindel, J.A.; Campbell, M.R.; Meyer, K.A.; Mamer, E.R.J.M. Production of a YY male brook trout broodstock for potential eradication of undesired brook trout populations. *N. Am. J. Aquac.* **2016**, *78*, 72–83. [CrossRef]
105. Schill, D.J.; Meyer, K.A.; Hansen, M.J. Simulated effects of YY-male stocking and manual suppression for eradicating nonnative brook trout populations. *N. Am. J. Aquac.* **2017**, *37*, 1054–1066. [CrossRef]
106. Thresher, R.E. Autocideal technoogy for the control of invasive fish. *Fisheries* **2008**, *33*, 114–121. [CrossRef]
107. Thresher, R.W.; Hayes, K.; Bax, N.J.; Teem, J.; Benfey, T.J.; Gould, F. Genetic control of invasive fish: Technological options and its role in integrated pest management. *Biol. Invasions* **2014**, *16*, 1201–1216. [CrossRef]