The effectiveness of non-native fish removal techniques in freshwater ecosystems: a systematic review

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Abstract

In aquatic systems, biological invasions can result in adverse ecological effects. Management techniques available for non-native fish removal programs (including eradication and population size control) vary widely, but include chemicals, harvest regimes, physical removal, or biological control. For management agencies, deciding on what non-native fish removal program to use has been challenging because there is little reliable information about the relative effectiveness of these measures in controlling or eradicating non-native fish. We conducted a systematic review, including a critical appraisal of study validity, to assess the effectiveness of different non-native fish removal methods, and to identify the factors that influence the overall success rate of each type of method. We found 95 relevant studies, generating 158 data sets. The evidence base was dominated by poorly documented studies with inadequate experimental designs (76% of removal projects). When the management goal was non-native fish eradication, chemical treatments were relatively successful (antimycin 75%; rotenone 89%) compared to other interventions. Electrofishing and passive removal measure studies indicated successful eradication was possible (58% each respectively) but required intensive effort and multiple treatments over a number of years. Of these studies with sufficient information, electrofishing had the highest success for population size control (56% of data sets). Overall, inadequate data quality and completeness severely limited our ability to make strong conclusions about the relationships between non-native fish abundance and different methods of eradication and population control, and the factors influencing the overall success rate of each method. Our review highlights that there is considerable scope for improving our evaluations of non-native fish removal methods. It is recommended that programs should have explicitly stated objectives, better data reporting, and study designs that (when possible and appropriate) incorporate replicated and controlled investigations with rigorous, long-term quantitative monitoring. Future research on the effectiveness of non-native fish removal methods should focus on: (1) the efficacy of existing or potentially new removal measures in larger, more complex environments; (2) a broader range of removal measures in general, and (3) phenotypic characteristics of individual fish within a population that fail to be eradicated or controlled.

Keywords: alien invasive species, restoration, nonindigenous species, invasive species, invasion biology, evidence-based policy.

Introduction

In aquatic systems, biological invasions can result in adverse ecological effects (Gozlan et al. 2009; Ricciardi and MacIsaac 2011). Invasive species threaten biodiversity (Vitousek et al. 1997; Sala et al. 2000; Koel et al. 2005) and impose considerable economic costs (Pimentel et al. 2005), placing increased demands on policy-makers, resource managers, and scientists (Simberloff et al. 2013). The introduction and spread of aquatic invasive species can occur by natural or human pathways, including: shipping networks and canals (Ruiz et al. 1997; Levine and D'Antonio 2003), escapes from aquaculture, aquaria and ornamental trade (Padilla and Williams 2004), stocking (Gozlan et al. 2010), bait bucket transfers (Ludwig and Leitch 1996), and recreational boating (Clarke Murray et al. 2011). Additionally, the secondary spread of introduced species poses considerable challenges for resource managers (Fredenberg 2002; Lintermans 2004; Vander Zanden and Olden 2008).

Options for managing non-native fish species can include no action, control and/or containment, population extirpation, and/or species eradication (Varley and Schullery 1995). Containment, such as implementing barriers, is used to prevent the spread of non-native species into novel environments (Fausch et al. 2006; Finnoff et al. 2007; Peterson et al. 2008; Britton et al. 2011*a*). However, where containment is not possible or has not been successful, eradication has been proposed as a valid option for managing biological invasions (Rinne and Turner 1991; Genovesi 2005). Eradication is the elimination of whole fish populations or fish species from distinct habitats or bodies of water (Gresswell 1991), and is usually aimed at new introductions that are confined to localized spatial areas (Britton et al. 2011*b*). Eradication approaches tend to be targeted, for example, by exploiting vulnerable periods in the life cycle (Buhle et al. 2005; Syslo et al. 2013) or by focusing on areas of high abundance (Meronek et al. 1996). When complete eradication is infeasible or unsuccessful, control methods can be implemented to suppress the non-native population either through selective removal or eradication of determinate populations from lentic habitats where there is high risk of natural dispersal into lotic habitats (Britton and Brazier 2006).

The types of fish management techniques available to resource managers to implement fish eradication and population control programs for non-native species can vary widely. Methods include chemical treatments, harvest regimes, physical removal, or biological control (Meronek et al. 1996). The effectiveness of chemical treatments (e.g., rotenone, antimycin) depends on environmental conditions (e.g., water temperature, depth, pH, discharge, target fish species, hydrology, substrate composition, and areas of groundwater recharge; Finlayson et al. 2000); there are also concerns of unintended consequences when non-target species are affected by chemical treatments (Vinson et al. 2010). Harvest regimes can include intentional over-fishing (e.g., gill netting and angling) of target species (Paul et al. 2003; Syslo et al. 2011; Gaeta et al. 2015) or modification of angling regulations (e.g., favour overharvest of target species). Physical removal techniques can include traps, electrofishing, and/or netting programs, and biological controls can include the introduction of predators, intraspecific manipulation, or targeted pathological reactions (Davis and Britton 2015). When implementing fish management programs, risk analysis assists selection of the commensurate strategy and its likelihood of success (Britton et al. 2011*a*). The risk analysis includes identification and assessments of hazards, including predicting the likelihood and severity of adverse effects (Koel et al. 2010; Copp et al. 2016).

The success of non-native fish management approaches can vary greatly depending on objectives, such as whether control, eradication, or containment (amongst others) was the ultimate goal of the project. As can be expected given the complexities of the natural environment, success can be difficult to quantify and some approaches can be unsuccessful despite best efforts (Simberloff et al. 2013; Rinne and Turner 1991; Meronek et al. 1996). Failure of non-native fish management techniques can occur because of a number of factors, including ineffective capture techniques (e.g., size-specific efficiencies), habitat complexity (e.g., areas of refuge and plant density) and water-body size, species-specific factors (e.g., size and habitat preferences), and physical water properties (e.g., water chemistry, temperature, and water depth; Britton et al. 2011*b*). Determining the outcomes of management interventions, especially when restoration of freshwater ecosystems is a goal (e.g., to eradicate non-native target fish species from a specific waterbody or return the waterbody to its pre-invasion state), requires long-term evaluation and assessment in relation to meeting the objectives (Rinne and Turner 1991; Meronek et al. 1996; Britton and Brazier 2006). Post-program evaluation and assessment is required not only to determine the effectiveness of techniques but also to explore the cost-effectiveness and cost/benefit of each strategy.

There have been a number of traditional reviews conducted on the efficacy of fish management measures (e.g., Corfield et al. 2007; Ayres and Clunie 2010; Halfyard 2010; Kolar et al. 2010; Britton et al. 2011*b*). Some reviews have primarily focused on removal of ‘undesirable’ (and not necessarily non-native) fish species (e.g., Schuytema 1977;

Meronek et al. 1996; Wydoski and Wiley 1999), a particular type of management intervention (e.g., chemicals: Lennon 1970; Rinne and Turner 1991; Rowe 2001; Rayner and Creese 2006; Clearwater et al. 2008), or on interventions for a particular management objective i.e., prevention or containment of non-native fish (e.g., Elkins et al. 2009; Sorensen 2015). While these reviews are valuable and may be reliable, they are also susceptible to a range of biases that can reduce their reliability (Petticrew and Roberts 2008). Here, we use a 'systematic review' approach (Pullin and Stewart 2006) to evaluate the existing literature base to assess the effectiveness of different non-native fish eradication and population control methods. For the purpose of this review we collectively refer to these methods as "removal measures". What sets apart systematic reviews from most traditional reviews in the field of applied ecology is that systematic reviews provide a rigorous, objective, and transparent methodology to assess the impacts of human activity and effectiveness of policy and management interventions (Roberts et al. 2006; O'Leary et al. 2016; Cooke et al. 2017; CEE 2018).

Specifically, the objective of the systematic review was to evaluate the existing literature base to assess the effectiveness of different non-native fish removal methods, and to identify the factors that influence the overall success rate of each type of method, in order to better inform management agencies who routinely have to decide when, where and how non-native fish eradication programs should be implemented. The review also aimed to identify knowledge gaps and suggest areas for new research.

Approach

Search strategy and study selection

The search strategy for this review was structured according to the collaboration for environmental evidence's guidelines (CEE 2013) and followed that published in the protocol (Donaldson and Cooke 2016), with changes stated in Text S1. The search strategy was developed to include a variety of article types, including primary literature in peer-reviewed journals and grey literature (e.g., theses, government papers, organisation reports, and consultant reports, etc.) and used 5 online publication databases [(1) Waves (now the Federal Science Library), (2) ProQuest Dissertations & Theses Global, (3) Science.gov, (4) ISI Web of Science Core Collection, and (5) Scopus; Nov 2016], and the search engine Google scholar (first 500 hits; Dec 2016). Whenever possible, the following search string was applied throughout the searches (in Web of Science format): [(Fish*) AND (Invasive$ OR "Non Native$" OR NonNative$ OR Alien$ OR Exotic$ OR introduced OR "non indigenous" OR Nonindigenous OR IAS OR "Invasive species" OR "Alien invasive$") AND ("Fresh water" OR Freshwater OR Stream$ OR Water$ OR River$ OR Lake$ OR Reservoir$ OR Pond$) AND (Hydraulic OR Screen* OR Weir$ OR Net OR Nets OR Netting OR Gill OR Trammel OR Hoop OR Trap OR Cast OR Lift OR Sein* OR Trawl* OR Electrofish* OR Electric OR Cull OR Piscicide$ OR Rotenone OR Antimycin OR Fintrol OR Explosive$ OR Primacord OR Biocide OR Angl* OR Trotline$ OR "Rod and reel" OR "Limb lin*" OR Limblin* OR "De water*" OR Dewater* OR "Drawn down" OR Drawndown OR Pump*) AND (Restor* OR Rehabilitat* OR Remov* OR Eradicat* OR Control* OR Suppress* OR Reduc* OR Renovat* OR Exclusion OR Exclud*)]. Full details of the search strings used and the number of articles found from each source are provided in Text S2. English search terms were used to conduct all searches in all databases and search engines. No date, language, or document type restrictions were applied during the searches.

We also searched for relevant information on 28 specialist organization websites (see Text S3 for list of websites) in February 2017 using the abbreviated search terms [i.e., search strings (1) fish AND eradication; (2) invasive AND eradication; (3) introduced AND eradication]. Page data from the first 20 search results for each search string were extracted (i.e., 60 hits per website), screened for relevance, and searched for links or references to relevant publications, data and grey literature. Potentially useful documents that had not already been found using publication databases or search engines were recorded.

In addition, reference sections of accepted articles and 60 relevant reviews (see Table S1 for a list of reviews) were hand searched to evaluate relevant articles that were not found using the search strategy. Stakeholders and advisory team members were consulted for insight and advice for new sources of information (i.e., Parks Canada, Canadian Wildlife Federation, United States Geological Survey, and British and Australian academics). We also issued a call for evidence to target sources of grey literature through presentations at meetings and conferences (e.g., Ontario Biodiversity Summit, Fisheries and Oceans Canada headquarters, American Fisheries Society – Ontario Chapter Annual Meetings), relevant list serves (e.g., Canadian Conference for Fisheries Research, American Fisheries Society), and social media (e.g., Twitter, Facebook) and email, to alert the community of this systematic review and to reach out to area experts for further recommendations and for provision of relevant unpublished material (summer of 2016 & February 2017).

Article screening and study inclusion criteria

Articles found by searches in databases and search engines were screened in two distinct stages: (1) title and abstract, and (2) full text. Articles or datasets found by other means than database or search engine searches (i.e., specialist website or other literature searches) were entered at the second stage of this screening process (i.e., full text). Prior to screening the full set of results at each stage, consistency checks of reviewers were undertaken on a subset of articles and discrepancies discussed (see Text S4A for further details). A list of all articles excluded on the basis of full-text assessment is provided in Table S2, together with the reasons for exclusion.

Each study had to pass each of the following criteria in order to be included:

1. Relevant subjects

The relevant subjects of this review were non-native freshwater fish. We did not consider articles that implemented a management technique with the goal of eradicating all fish species, including native species, or when targets were only identified as 'undesirable', 'trash', or ‘pan’ fish species. The focus on non-native freshwater fish for this systematic review primarily stemmed from its identification as a priority for the Parks Canada Agency (stakeholders), a federal government agency in Canada mandated with protecting the natural and cultural heritage of sites (i.e., national parks and reserves, national marine conservation areas and national historic sites). The maintenance and restoration of ecological integrity represent core principles of Parks Canada such that they employ biologists and restoration specialists tasked with engaging in activities such as fish eradication and population control of non-native species. We acknowledge that articles reporting information on removal measure efficacy for non-native fish species may also contain relevant information in certain contexts; however, they do not directly address our main research question. We also only considered wild or stocked systems, excluding articles related to management in aquaculture, hatcheries, and nurseries. Note, we excluded articles on sea lamprey (*Petromyzon marinus*) from the review for a number of reasons: (1) there are extensive multi-national control programs ongoing (e.g., the Laurentian Great Lakes) that are not rivaled for any other freshwater fish species (reviewed in Siefkes 2017); (2) the amount of money that has been applied to their control is not comparable to other species thus far, and (3) their taxonomy (as agnathans – one of the few freshwater jawless fishes) and ecology (i.e., parasitic life style) is such that it makes it difficult to compare to other fish species. In this regard, our search terms were not developed to capture literature on lamprey specifically.

2. Relevant types of interventions

The intervention refers to a fish eradication or population control method. Measures could include (but not limited to) one or more of: (1) chemical treatment; (2) harvest regimes (i.e., intentional over-fishing of target species, or modification of angling regulations); (3) physical removal; (4) biological control [e.g., introduction of predators, intraspecific manipulation (i.e., adding competitor species), sterilization (i.e., chemical or genetic manipulation), or targeted pathological reactions]; (5) environmental (e.g., lowering water level); (6) other (e.g., explosives), or (7) any combination of the above methods. This review focused only on measures aimed at eradication or population control of non-native fish. We excluded articles that implemented measures to prevent the introduction of a non-native fish species or to contain the spread of non-natives (e.g., barrier screens, behavioural avoidance measures i.e., use of food/competitor/predatory odors or chemosensory cues, lights). Furthermore, we excluded articles that only presented preliminary test findings of a larger project or a stepping-stone project that was used to determine whether a management technique or product could be used as a removal measure in the field. For example, Schill et al. (2016) suggested a potential alternative to manual or piscicide fish removal in the use of the Trojan Y Chromosome (TYC) program in which hatchery-produced genetically YY male fish would be regularly released into an undesired population over time, skewing the population towards 100% males, theoretically resulting in wild population extirpation. However, this was just a preliminary study in the development of TYC technology and did not evaluate the method as an eradication technique. These types of excluded articles could also include, for example, laboratory studies determining the toxicity level requirements (i.e., exposure concentrations to chemicals) and/or environmental variables that may affect eradication technique performance (e.g., Marking et al. 1983).

3. Relevant types of comparators/study designs

This review compared outcomes based on articles that used Before-After (BA), Control-Impact (CI), or a combination of these comparisons Before-After-Control-Impact (BACI) and randomized controlled trial (RCT) study designs. Relevant comparators included: (1) similar sections of the same waterbody with no intervention (i.e., upstream condition); (2) separate but similar waterbodies with no intervention (i.e., waterbodies with non-native fish present but have not had any fish management projects conducted in them); (3) before intervention data within the same waterbody, or (4) an alternative intervention type conducted on the same or different waterbodies. Theoretical studies (e.g., individual-based models or population viability analysis), review papers and policy discussions were excluded.

4. Relevant types of outcomes

The outcome of interest consisted of qualitative and quantitative information on the measured effect of treatment. Measured effect of treatment generally needed to indicate some change in abundance of the target species relative to before treatment or control. We used a broad definition of abundance to include population size (or relative size), population density (or relative density), number of fish removed (with no estimate of population size/density), removal efficiency, catch per unit effort (CPUE), biomass (e.g., total weight of fish removed), and species presence or absence from an area or management unit (as an index of high vs. low abundance for population control, or the success/failure of an eradication attempt).

Additionally, only full text articles written in English or French were included.

Critical Appraisal

All articles that had passed full-text screening were critically appraised to assess whether the evidence was valid for answering our review question. This critical appraisal process was used to assess the absolute and relative importance of different sources of bias and data validity elements (e.g., temporal and spatial replication). Here and throughout this review, we refer this assessment of susceptibility to bias, as study validity. This critical appraisal was based on the entire evidence found on an individual removal *study*, not on individual articles. In these situations, we cite the article (i.e., primary study source) with the most comprehensive information (or in some cases, the most recent publication) and identify supportive articles as supplementary articles (see Table S3 for a list of supplementary articles and Text S4B for further details of critical appraisal). If a study contained more than one project (i.e. differed with respect to one or more components of critical appraisal; see Table 1), each project received an individual validity rating and was labelled in the data extraction table with letters (e.g., Ertel et al. 2017 “A/B/C/D”). Critical appraisal was conducted using a predefined framework developed to: (1) assess the risk of bias across a range of variables for each study (see Table 1), and (2) assign each project with a critical appraisal category based on these variables. The framework was based on an evaluation of the following criteria: study design (BACI, BA, CI), temporal and spatial replication (see Text S4C for definitions of pre-, during- and post-removal periods), measured outcome (quantitative, quantitative approximation, semi-quantitative, or qualitative), intervention application coverage (appropriateness of intervention based on species/system), control matching (how well matched the intervention and comparator sites were in terms of habitat type), and confounding factors (environmental or other factors that differ between intervention and comparator sites). Each criterion was scored at a ‘high’, ‘medium’, ‘low’, or ‘very low’ level based on the framework outlined in Table 1. The project was given an overall ‘very low’ validity if it scored very low for replication. The study was given an overall ‘low’ validity if it scored low for one or more of the criteria. If the project did not score low for any of the criteria, it was assigned an overall ‘medium’ validity. If the study scored only high for all of the criteria, it was assigned an overall ‘high’ validity (see Table S4 for assessment for the individual studies).

Data extraction strategy

Data on potential effect modifiers and other metadata were extracted from the included primary study source or their supplementary articles whenever available. Data extracted included: study location (e.g., country, longitude, latitude, waterbody name), and species information, the applied intervention(s) and its frequency, the outcomes, the methodology and other potentially confounding factors that were identified as possible reasons for heterogeneity (i.e., waterbody type, area, depth, open or closed waterbody system, time since invasion, seasonality of intervention application(s), presence of containment measures prior to or during study (e.g., barrier screens), study design, duration of outcome sampling). We also gathered general study summary information, i.e., brief statement of study objective, categorized goal of the applied intervention(s) as stated by authors, and summarized results (Table S5). See Text S4A for details of data extraction consistency checks.

The data extraction form was piloted on a representative sample of studies, to represent the range of available studies. At this stage, it became apparent that there was a lack of studies reporting useful quantitative data for both the intervention group and the comparator group. For example, it was common for studies to only have qualitative information for the outcome measure prior to intervention (i.e., presence of a non-native fish species) and then have a quantitative value after intervention (i.e., number of fish killed). This precluded our ability to conduct formal synthesis of quantitative outcomes across studies, i.e. meta-analysis. Therefore, regarding the assessment of intervention effectiveness, each study (or data set within a study) was given an effectiveness rating by the reviewer (Table 2). These ratings were based on: (1) a comparison of quantitative data from the comparator group and the intervention group (when possible); or (2) author’s conclusions on the success/failure of the intervention(s) for the stated goal (Table 2). If neither quantitative data, nor the author’s conclusions on the success of the intervention(s) were provided, the effectiveness rating was classed as undetermined. This effectiveness rating was the basis for the intervention effectiveness variable used for narrative synthesis.

Findings

Review descriptive statistics

Literature searches and screening

Fig. 1 shows the step-by-step results from the search and screening process. Our literature search from the five scientific databases and Google Scholar yielded 2,561 unique records after duplicate removal. After full-text screening, 56 relevant articles met our inclusion criteria from the publication databases and search engine. Another 60 relevant articles were included after full-text screening from specialist websites, bibliographies of relevant reviews, and other searches. A further 24 articles were found from searching included article bibliographies, resulting in 140 articles that underwent data extraction and study validity assessment (Fig. 1). After exclusions and combining overlapping articles, 95 ‘studies’ were included in the review synthesis (see Table A1 and Table S3 for a list of the included primary study sources). These 95 studies generated 158 data sets (i.e., studies could have >1 datasets if they targeted more than 1 non-native species, and/or evaluated different removal measures in different waterbodies).

Sources of articles used for data extraction and validity assessment

The following descriptions are based on the primary (or only) source of the study information (i.e., the most comprehensive source, in cases where supplementary articles were identified).

Fifty-six of the primary articles reported on research that was directly or indirectly related to removal of at least one non-native freshwater fish species and were published in peer-reviewed journals. Twenty-five are better described as monitoring or project reports from government or consultant groups. The remaining 14 articles were in the form of conference proceedings (6), theses (3), newsletters (2), a book chapter (1), a website (1), and a conference presentation (1).

Primary articles were published from 1939 to 2017. Only 10 of the 95 articles were published before 1990. Years of publications were distributed fairly evenly over the period of 1980–2004, after which an increase in the number of articles can be seen over the more recent years (2005-2017) (see Fig. 2).

Study validity assessment

Validity assessments were conducted for individual removal projects, of which there were 106 identified from the 95 studies (see Table S4). For the majority of the projects, we found the validity of the available evidence to have very low (22 of 106 projects) or low (58 projects) study validity (very high or high susceptibility to bias). Only 1 project was classified as having high study validity (Closs et al. 2001). In the remaining 25 projects, we classified the susceptibility to bias as medium (see Table 3). Projects were assessed as having very low study validity when there was only 1 before or after year assessment period and that period was >5 years either prior to or following intervention, or there was insufficient information on the before or after assessment period i.e., no pre-intervention dates were provided. The majority of projects classified as having low study validity had at least one qualitative outcome measure, lacked sufficient information on the application coverage of the intervention, and/or had low spatial/temporal replication (i.e., 1 BA or CI replicate) (Table 3). Projects of medium susceptibility to bias were assessed as such primarily because they used a BA, CI, or incomplete BACI design [i.e., data is missing for certain components of the design (e.g., missing before data for control sites), preventing the data from quantitative analysis using the full BACI design], had moderate spatial/temporal replication, and/or used quantitative approximations for both intervention group and comparator outcome measures (Table 3).

Based on our study validity assessments, the quality of the available evidence seems to have improved during the late 1980's; however, the proportion of the lower quality studies in a given time period has stayed relatively similar since then (Fig. 3).

Narrative synthesis

Study descriptions

Project goal. – Nearly half of the data sets included in this review had a goal of non-native fish eradication (77 of 158 data sets). Control of non-native fish population size (i.e., a reduction in abundance, density, and biomass) was the goal of 69 of the data sets (44%). For 12 data sets (8%) either eradication or population control was stated as the goal of the project, or it was unclear whether complete eradication was the actual goal since partial removal was considered to be a beneficial outcome. In 55 of the data sets, a change in species composition (i.e., a shift from non-native to native fish species, or an increase in native species abundance) was also identified as a goal of the project. Furthermore, in 2 data sets, a change in target species size was stated as a goal in addition to the suppression of non-native fish population size. For the purposes of this review, we only focus our synthesis on information related to non-native fish eradication or population control i.e., we do not summarize information on population structure (e.g., length, age, weight) or composition.

Geographical location. – Most of the studies in this review were performed in North America (62% of data sets) – more than 80% of which were in the United States of America (USA) –, with some carried out in Oceania (26%), Europe (11%), and Africa (1%) (Fig. 4). When considering all studies across North America, there was nearly a 50/50 split between eradication and control goal-oriented projects. However, when isolating Canadian from American projects, we found that the goal of most projects in Canada was non-native fish eradication (73% of datasets), whereas, the focus was slightly more on population control in the USA (54% of datasets) (Fig. 4). Within Europe, the most frequently reported project goal was population control (58% of datasets); whereas, eradication was most commonly stated as the goal of projects in Oceania (69% of datasets).

Population. – Studies targeted 42 non-native fish species from 30 genera for removal. The most common targeted non-native fish were brook trout (*Salvelinus fontinalis*; 19 studies, 29 data sets), rainbow trout (*Oncorhynchus mykiss*; 13 studies, 22 data sets), common or koi carp (*Cyprinus carpio*; 13 studies, 18 data sets), smallmouth bass (*Micropterus dolomieu*; 7 studies, 8 data sets), northern pike (*Esox lucius*; 6 studies, 9 data sets), brown trout (*Salmo trutta*; 6 studies, 7 data sets), and European perch (*Perca fluviatilis*; 6 studies, 6 data sets). Less than 19% of studies targeted more than 1 non-native fish species for removal. The majority of studies implementing a removal measure were conducted within lakes/ponds (43% of studies), and rivers/streams/creeks (42%), with a few in reservoirs (11%), wetlands (3%), and canals (1%).

In the USA, studies targeted 24 non-native fish species from 17 genera, the most common being rainbow and brook trout, and common carp (Table S6). Seven non-native fish species were targeted for removal in Canada; the most frequently targeted were brook trout (Table S6). Eight non-native fish species were targeted for removal in Europe, the most common being the topmouth gudgeon (*Pseudorasbora parva)* (Table S7). In Australia and New Zealand, 9 and 5 non-native fish species were targeted respectively, with the majority of species including common carp, European perch, and goldfish (*Carrasius auratus*) (Table S7).

Intervention. – The vast majority of studies implemented one main intervention to either eradicate or control population size of a non-native fish species (70% of data sets; Fig. 5).

Of the studies that used one main intervention, the most commonly used removal techniques included measures categorized as either physical (53% of data sets) or chemical (38%). Studies that only used harvest, environmental, or biological type measures were used less frequently (6%, 2% and 1%, respectively). Physical and chemical measures were most frequently combined with another measure (55% and 20% of data sets, respectively) either simultaneously or consecutively than other removal measure categories.

Of the studies that implemented physical removal measures (either alone or in combination with another measure), the majority used electrofishing by boat or back-pack, or passive removal measures including hoop-, gill-, or fyke-nets, or traps (Table 4). The majority of studies used chemical treatments for removal using rotenone, followed by antimycin (trade name, Fintrol®) (Table 4). Only two types of harvest measures were used and with the same frequency (i.e., angling and a combination of passive and active netting; Table 4). For biological control measures, predator introduction was the only measure utilized. Six studies used an environmental measure in the form of lake dewatering, either alone (2 data sets) or in combination with another measure (5 data sets). Only one study used an alternative form of removal through the use of explosives, and only in combination with other measures (Table 4).

Just over 46% of data sets that implemented a removal measure, also included containment measures (i.e., pre-existing measures before start of study, implemented during study period, or natural barriers) to prevent/reduce the spread of non-native(s). For studies that reported accurate information on the time since invasion (i.e., date of discovery of a non-native in the study waterbody to the start of the removal program; 59% of data sets), 12% initiated removal attempts within the first year of discovery.

Study design and comparator. – The availability of outcome data from different assessment periods of each of the included removal studies is shown in Fig. S1-S3, along with study validity assessments. Of the 158 data sets, 136 used – in a broad sense – a BA design. In 73 of these data sets, studies reported data collected before and during the intervention, but not afterwards (BD designs); in nearly 44% of these BD data sets, the actual before date period was either not stated or data were collected more than 5 years prior to the start of the intervention (deficient BA comparison). In 63 other BA data sets, outcome data were reported before, during and after intervention (BDA designs); 14% of these BDA had a deficient BA comparison. Another 17 of 158 data sets used a BACI design; 12 of which did not report outcome data after the intervention (BDCI design) and 5 which did report after data (BDACI design). The remaining 5 data sets (3 articles) in the review employed a CI design (Control-Impact).

For designs that incorporated control sites (i.e., CI and BACI designs), most data sets used control sites in the form of the up- or down-stream condition within the same waterbody as the impact site(s) with the applied intervention (77% of CI and BACI data sets). For the remaining CI and BACI data sets, control sites were different waterbodies with no intervention (i.e., waterbodies with non-native fish present but had not had any fish management projects conducted in them).

For study designs that reported before intervention data, the majority collected outcome data ≤1 year prior to implementing a removal measure (81% of BA and BACI design data sets). The available outcome data for the before period ranged from 1 to 11 years (Fig. S1-S3). For designs that collected 'true' after intervention outcome data, 49% of data sets only did so ≤1 year after the intervention was applied. The available outcome data for the 'true' after period ranged from 1 to 19 years (Fig. S1-S3). In all cases of the CI designs, comparisons were made during the intervention periods i.e., there were no 'true' after monitoring periods.

The number of control sites used in CI and BACI designs ranged from 1 to 4; 55% of data sets only used 1 control site. Although the number of impact sites used in these studies had a greater range (1-13) most (55% of data sets) only used 1 impact site.

Outcomes. – The outcomes that we extracted from studies were dominated by semi-quantitative observations (53% of data sets), whereby the outcome measure for the comparator group was the presence of a non-native fish (a qualitative measure), and the outcome measure of the intervention group was some form of a quantitative abundance measure [e.g., the number of fish killed, abundance (or density), catch per unit effort (CPUE), biomass]. For studies that collected quantitative outcome measures (39% of data sets), nearly 43% of these reported more than one outcome measure indicating some change in 'abundance' of target species with the intervention group relative to the comparator group. The three most commonly reported outcome measures were: (1) the number of fish killed (88 cases); (2) an estimate of population size (48 cases); and (3) CPUE (32 cases). Relatively few studies reported outcomes in the form of abundance (or density) (11 cases), percent removal efficiency (10 cases), or biomass (e.g., total weight of fish removed/recovered) (5 cases). Qualitative observations were made in 9% of data sets.

Evidence of effectiveness

Chemical treatment for eradication

Nearly 26% of all data sets used a fish toxicant alone for eradication attempts on non-native fish (i.e., no other main interventions were used). The two toxicants used were antimycin A (Fintrol®) (6 articles, 9 data sets) and rotenone (23 articles, 32 data sets), both of which are considered general-use piscicides (i.e., toxic to all fish). Study validities for effective antimycin data sets of eradication were distributed fairly evenly over the very low, low, and medium assessments; whereas, the frequency of low validity studies was higher than either the very low or medium assessments for effective rotenone data sets (Fig. 6*a* and *b*).

Antimycin. – Antimycin was reported effective in eradicating a non-native fish in 75% of data sets (Fig. 6*a*). Geographically, studies implementing antimycin alone were located in a few US Rocky Mountain and Southwest states, and a single study in eastern Canada conducted in the mid 1970s. Two studies applied the toxicant in lakes (Hooper and Gilbert 1978; Baker et al. 2010); whereas, all others were implemented in perennial creeks. Only a single study with 2 data sets used a BACI study design for evaluations of antimycin (Marks et al. 2010); all others employed a BA study design. The number of applications of antimycin varied from 1 to 3, with 78% of the antimycin data sets applying more than 1 application, and over varying times of the year. The number of 'true' post-monitoring years (not including the last during intervention year) ranged from 0 to 3 years after the last (or only) application of antimycin, most were ≤1 year after treatment (56% of antimycin data sets). One study (Meffe 1983) was unsuccessful in eradicating a non-native fish from a shallow spring after a single antimycin treatment. See Table S8 for summary characteristics and results of studies implementing antimycin alone for eradication of a non-native fish species.

Rotenone. – Rotenone was reported effective in eradicating a non-native fish in 89% of data sets (Fig. 6*b*). Rotenone was more widely and commonly used internationally than antimycin. The majority of rotenone treatments occurred in lakes (41 % of rotenone data sets), followed by ponds (25%), creeks (19%), rivers (6%), reservoirs (6%), and lagoons (3%). When looking at national trends, the number of successful eradications was greater than unsuccessful eradication attempts in all countries except Canada, where there was an equal number of each. For the countries that most commonly used rotenone, the percentage of effective eradication attempts with rotenone use was greater for USA than for Australia (87% vs. 44%, respectively). In one study, the eradication attempt was rated as partly effective since the rotenone did result in eradication in all 7 streams treated; however, the non-native later re-established in one creek and the lower reaches of another, as a result of a suspected deliberate re-introduction by anglers (Lintermans and Raadik 2003). Additionally, the eradication effectiveness was classified undetermined for one data set in another study (i.e., *Carrasius auratus*, Hall 1988), where two non-native fish species were targeted for complete eradication but post-treatment results were only presented for one of the two species.

There did not appear to be any patterns between rotenone effectiveness and the number or seasonality of application(s), species, or water-body type. Furthermore, there were no discernible patterns between rotenone effectiveness and the presence of containment measures (e.g., barrier screens), either implemented prior to or during the study, or those that occurred naturally (e.g., waterfall), or outcome category. All studies using rotenone employed a BA study design. Rotenone was applied most often only once to a waterbody (75% of data sets), but up to two times; however, for two studies, insufficient details were provided on the number of applications (Swanson 1971; Beamesderfer 2000). Although rotenone treatment was carried out at all times of the year, fall was the most common season for application for studies both in the northern and southern hemisphere (49% of reported applications). The number of 'true' post-treatment sampling years ranged from 0 to 19 years after the last (or only) application of rotenone, but the majority were conducted for ≤1 year after treatment (59% of data sets). Information on area or length of the waterbody treated was often not reported in these studies, limiting the assessment of the impact of this variable on rotenone effectiveness. See Table S9 for summary characteristics and results of studies implementing rotenone alone for eradication of a non-native fish species.

Chemical treatment for population size control. – Only three data sets from 2 studies implemented a chemical intervention alone to evaluate the efficacy of population size control of a target non-native fish (Fig. 6*c* and *d*). One study targeting Eurasian ruffe (*Gymnocephalus cernuus*) treated two rivers in Minnesota, USA, with TFM (3-triflouromethyl-4-nitrophenol), a taxon-specific chemical used for control of sea lamprey (Boogaard et al. 1996). Comparison of pre-treatment and post-treatment CPUEs indicated that the ruffe population was reduced by 97% (Brule River) and 54% (Amnicon River) with the use of a single application of TFM. In both instances, post-treatment monitoring was short term (i.e., Brule River: ~ 2 weeks and again 2 months after treatment; Amnicon River: 5 days after treatment) and study validities were classified as low because of small temporal repetition. In another study, Beamesderfer (2000) presented case studies, one of which was not previously published that described – in very little detail – the chemical treatment of the Tenmile Lakes system in Oregon in 1968 with rotenone for bluegill (*Lepomis macrochirus*). Although it was reported that treatment had initially been effective, 19 years of post-treatment monitoring showed bluegill quickly repopulated (Beamesderfer 2000). Despite the long-term post-treatment monitoring, study validity was classified very low because of the limited information reported in the study.

Physical removal for eradication

Of the included data sets, 15% implemented a single physical removal measure, not in combination with any other main interventions, for eradication of a non-native fish. Two general categories of physical removal measures, electrofishing (7 studies, 12 data sets), and passive netting or trapping (6 studies, 12 data sets), were used. In general, the distribution of study validities across effectiveness ratings were similar between eradication attempts using electrofishing and passive netting/trapping measures (Fig. 6*e* and *f*). The majority of studies, whether reporting effective and ineffective eradications, were assessed as having low study validities.

Electrofishing. – Electrofishing was reported effective in eradicating a non-native fish in 58% of data sets (Fig. 6*e*). All studies applying electrofishing alone in an attempt to eradicate a non-native fish species did so using backpack electrofishers. There were no geographical differences in reported effectiveness between regions; most of these studies were conducted in the USA (83% of data sets).

Successful eradications used a greater number of treatments to a waterbody (mean: 10.9 ± 2.57 SD) than unsuccessful eradication attempts (4.0 ± 2.34) (t-test: t=2.15, df

=10, p= 0.057). It should be noted that information on the number of times a waterbody was treated with electrofishing was not always clearly reported, but the approximate total number of times a waterbody was treated over the course of the intervention period (or treated until the non-native fish species was no longer captured) varied widely from 3 to 24. Effective eradications were monitored from 1 to 3 years after the last treatment or until fish were no longer captured. Unsuccessful eradication attempts were those that: (1) were investigating the effectiveness of electrofishing for either eradication or suppression of non-natives, or (2) it was unclear whether complete eradication was the actual goal since partial removal was considered to be a beneficial outcome.

There were no apparent patterns between electrofishing effectiveness and the number of during treatment years, the presence of a containment measure(s), or outcome category. Furthermore, all electrofishing evaluations were conducted in small lotic systems; only a single study occurred on a relatively larger river (Pacas and Taylor 2015). In all cases, non-native targets were trout species, the majority of which were brook trout (75% of data sets). Four data sets from two studies used a BACI study design for evaluations of electrofishing (Thompson and Rahel 1996; Kulp and Moore 2000); all others employed a BA study design. In all studies, electrofishing was applied for more than 1 year (range: 2-8 years). Table S10 for summary characteristics and results of studies implementing electrofishing alone for eradication of a non-native fish species.

Passive netting/trapping. – The frequency of data sets reporting successful eradication of a non-native fish species using passive netting/trapping was similar as for electrofishing (i.e., 58% of data sets each) (Fig. 6*f*). All but one study using passive removal measures alone in an attempt to eradicate a non-native fish species used monofilament gill nets with varying mesh sizes (i.e., 10-100-mm). Lozano-Vilano et al. (2006) was the only study that used standard minnow traps to target spotted jewelfish (*Hemichromis guttatus*) in Mexico. There were no differences in reported effectiveness among regions. Fifty percent of the data sets were from a single study (Knapp et al. 2007) which targeted non-native trout (*Oncorhynchus* sp., *Salvelinus* sp.) for removal from a series of mountain lakes in California, USA. Other studies were conducted in alpine lakes in Alberta Canada, Washington, USA, and another in California. Two other removal studies were from a lake complex in Waikato, New Zealand and a pond in Coahuila Mexico.

There did not appear to be any patterns associated with reported factors and eradication effectiveness using passive measures. Most passive netting/trapping studies have been conducted in relatively small [i.e., <90000 m^2 (or 9 ha)], shallow [i.e., ≤11 m] lenthic systems. All studies employed a BA study design, and the passive netting/trapping measure was applied for more than 1 year (range: 2-6 years). In most eradication attempts using passive removal measures, intensive, continuous netting was conducted throughout the year (75% of data sets). For the studies that did not conduct continuous netting/trapping, the number of removal treatments was 2 (Neilson et al. 2004) and 17 times (Lozano-Vilano et al. 2006) with vague information reported in another (i.e., Hoffman et al. 2004: “gill nets were placed in the lake from one to three days, once to several times a field season”). Post-treatment sampling ranged from 0 to 5 years after the last treatment or until fish were no longer captured. Despite the variability in the number of during and after treatment years, and the removal effort used for removals, there were no obvious patterns between these variables and the effectiveness of passive removal measures. Furthermore, containment measures were present in only 3 data sets, all in the form of natural barriers (Cony Lake: Knapp et al. 2007; Maul Lake: Knapp and Matthews 1998). All outcome categories were semi-quantitative with the exception of two studies that reported quantitative approximations (Parker et al. 2001) and quantitative (Neilson et al. 2004) outcome information for comparator and intervention groups. See Table S11 for summary characteristics and results of studies implementing passive netting/trapping alone for eradication of a non-native fish species.

Physical removal for population size control

Nearly 28% of data sets implemented a single physical removal measure for population size control of a non-native fish. Three general categories of physical removal measures were used: (1) electrofishing (15 studies, 34 data sets); (2) passive netting (4 studies, 4 data sets), and (3) active netting (3 studies, 6 data sets). Study validities for effective electrofishing data sets for population control were mostly very low or low assessments; however, there were a number of medium study validity assessments across effectiveness ratings for electrofishing (Fig. 6*g*). All active netting data sets, and 50% of the passive netting data sets, were assessed as low study validity (Fig. 6*h* and *i*).

Electrofishing. – Electrofishing was reported to be effective in reducing population size of a non-native fish in 56% of data sets (Fig. 6*g*). Studies using electrofishing alone in attempting to control non-native fish population size used either boat or back-pack electrofishing equipment (41% and 56% of data sets, respectively). All but three studies were conducted in the USA.

No discernible patterns were found between population control effectiveness and factors that could cause variation. Evaluations were conducted in mostly lotic systems such as rivers (53% of data sets) and creeks/streams (41%), and one study each in a weir (Thuesen et al. 2011) and a canal (Smith et al. 1996). A variety of non-native species were targeted for population control using electrofishing (14 species); the most common being trout species (i.e., rainbow and brook trout with 21% of data sets each). Similarly, a variety of study designs were used for evaluations of electrofishing, the most frequent design being BA (65% of data sets). Two studies (7 data sets) used a BACI design (Thompson and Rahel 1996; Propst et al. 2015), and three studies (5 data sets) used a CI design (Coggins 2008; Firehammer et al. 2009).

Unlike eradication-oriented studies, we did not observe a positive relationship between the number of effective data sets and the number of electrofishing treatments in population control studies. Furthermore, for all studies but one, there were no post-treatment sampling, meaning that there were always fish captured/ removed from each electrofishing treatment and/or that a different main intervention was never used at a later period to evaluate the effectiveness of electrofishing treatments in reducing population size of the target species. In the single study that did include after treatment monitoring, Meyer et al. (2006) returned to compare abundance and population dynamics of brook trout present after 3 years after treatment to the population in the treatment years.

There were three studies (5 data sets) that investigated the effectiveness of electrofishing for both eradication or population control, or that had unclear objective statements. As previously noted, when eradication was considered as the primary goal in these studies, all were found to be ineffective (see Table S10). However, when population control was considered, two of these same studies (4 data sets) were found to be effective in reducing populations size (Thompson and Rahel 1996; Caudron and Champigneulle 2011); only one study was found to be ineffective for both eradication and population control (i.e., Meyer et al. 2006).

There were a number of electrofishing studies rated as partly effective in reducing population size of a non-native fish (35% of the data sets). In a few of these cases, reductions in abundance were observed in some but not all waterbodies (or sections) (e.g., Franssen et al. 2014), or projects were still considered on-going (e.g., Scoppettone et al. 2012). For other studies, although a reduction in population size was reported, either compensatory reproduction of mature fish that survived removal efforts from previous years (e.g., Carmona-Catot et al. 2010) or immigration and recruitment pulses after treatment, subsequently resulted in increased numbers of younger fish (e.g., Saunders et al. 2015). Furthermore, although declines in non-native fish abundance with removal efforts were observed in some studies, the efficacy of the electrofishing removal was potentially confounded by external(s) systemic decline witnessed in comparator groups (e.g., Coggins 2008). See Table S12 for summary characteristics and results of studies implementing electrofishing alone for population control of a non-native fish species.

Passive and active netting. – Passive and active netting measures were reported effective in reducing population size of a non-native fish in 25%, and 67% of data sets, respectively. Both netting categories had relatively small sample sizes compared to the number of electrofishing cases (Fig. 6*h* and *i*), severely limiting analysis of the effectiveness of these measures for population control. Passive removal measures used to reduce population size included fyke (8-16 mm), and gill nets (10-38 mm). Seining was the only active removal measure used (i.e., 4.8 mm mesh sizes and conventional commercial seining using 35-mm square mesh size guided by Judas fish). Seventy percent of the data sets (4 studies) were conducted in the USA, with two studies in Europe, and a single study on a lake complex in Waikato, New Zealand. Passive and active removal measures have been investigated in a range of lake sizes (2500-120,000 m^2), and in two rivers (80.5-km reach; and three 16-km long reaches; Trammel et al. 2004). Both ineffective population control data sets were from this single study on rivers [93]. Only two studies employed a BACI study design (Trammel et al. 2004; Britton et al. 2010); all others used a BA design. Passive and active netting was applied for 1 to 20 years; however, this variable did not appear to be related to population control effectiveness. None of the passive or active removal measures were used continuously throughout the year, with 60% of the data sets conducted in a single season. From the available information, the number of removal treatments ranged from 1-15; with limited information reported in longest duration study (i.e., Bigelow et al. 2017). Interestingly, the single study with the greatest number of treatments was found to be ineffective in reducing population size. Trammel et al. (2004) suggested that although a reduction of non-native cyprinids was observed, this reduction was quickly offset by reproduction and that many smaller sized fish escaped through the seine nets. There were no apparent patterns between passive or active netting effectiveness for population control and the presence of a containment measure(s), or outcome category. See Table S13 for summary characteristics and results of studies implementing passive or active netting alone for population control of a non-native fish species.

Combinations of physical removals for eradication. – A few studies have combined various physical removal measures in an attempt to eradicate a non-native fish (6 studies), with 50% of them reporting successful eradications. Most of the included studies appear to be conducted in relatively larger lakes than the majority of the previously discussed studies [range: 23,400 - 53,100,00 m^2 (or 2.34-531 ha)]. The number of different types of measures used in combination was 2 or 5, both occurring in three studies each. All of these studies used at least one form of passive netting (i.e., gill, fyke, seine nets) or trapping (i.e., minnow or plastic bottle traps), and electrofishing.

Keeping in mind the small number of studies, there did not appear to be a pattern between the number of measures used or the combination of measures and eradication effectiveness. Reported information was limited on the number of applications and the time between implementation of each of the measures. From what information could be extracted, the combination of measures were implemented in relatively short duration of each other, if not simultaneously. Note here again, however, the two studies that investigated the effectiveness of a combination of physical removal methods for either eradication or population control, or that had unclear objective statements, were both found to be ineffective for eradication. See Table S14 for summary characteristics and results of studies implementing combinations of physical removal measures for eradication of a non-native fish species.

Combinations of physical removals for population size control. – There were greater number of studies using a combination of physical removal measures for non-native fish population control than for eradication (19 data sets, 15 studies). A combination of physical removal measures was reported effective in reducing population size of a non-native fish in 32% of data sets. Studies using multiple physical removal measures for population control were widely conducted across locales and waterbody types, and targeted a variety of non-native fish species; however, these factors did not appear to be associated with effectiveness. The number of different types of measures used in combination ranged from 2 to 5; the majority of which used two physical removal measures (74% of data sets). Combinations of measures were applied simultaneously. There did not appear to be a pattern between the number of measures used or the combination of measures, and population control effectiveness. See Table S15 for summary characteristics and results of studies implementing combinations of physical removal measures for population size control of a non-native fish species.

Biological treatment

Information on the effectiveness of biological control measures to eradicate or control population size of non-native fish is very limited. Only a single study included in the review used a biological control measure alone for removal of a non-native fish species. Koenig et al. (2015) investigated the effectiveness of introducing sterile tiger muskellunge (i.e., Northern pike *Esox lucius* x Muskellunge *E. masquinongy*) to eradicate or suppress brook trout populations in alpine lakes in Idaho, USA. Using a BACI study design, Koenig et al. (2015) compared CPUE from 13 stocked lakes – each stocked once and at a constant density of 40 fish/ha – to four control lakes 4-5 years after predator stocking. Complete eradication occurred in 4 of the 13 lakes within 2-5 years after stocking, and declines in CPUE were seen for both treatment and control lakes, resulting in partial effectiveness ratings for both eradication and population control (Fig. 6*j* and *k*). This study was assessed as having medium study validity.

Harvest regime treatment

Very few studies on harvest regime measures were included in the review (Fig. 6*l*). Two forms of intentional over-fishing for population control of target species were evaluated in relatively large water systems in the USA using: (1) gill, trammel and hoop nets, and seine hauls (MacNamara et al. 2016), and (2) angling (Larson et al. 1986). During a 3-year treatment period (c. 340 crew-days per year), MacNamara et al. (2016) reported that the overall density of silver (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*) decreased by over 40% and subsequently remained stable in different reaches of the Upper Illinois River, USA. In a comparatively short-duration (9-week) evaluation of an experimental fishery in Tennessee, USA, angling was found to reduce the density of non-native rainbow trout (Larson et al. 1986). However, the fishery was found to have minor immediate effect on the smallest size class of fish.

Environmental treatment

Two low validity studies used an environment measure alone, in the form of water body dewatering, for removal of a non-native fish species (Fig. 6*m* and *n*). These studies found that one attempt at pond dewatering was ineffective in eradicating the topmouth gudgeon (*Pseudorasbora parva*) in North Yorkshire, England (Pond 3: Britton et al. 2008), but effective in reducing the abundance of Eastern mosquitofish (*Gambusia holbrooki*) within multiple ponds in New South Wales, Australia.

Combinations of different removal measures

Nearly 13% of the data sets are evaluations of various combinations of removal measures (20 data sets from 16 studies). Comparisons of the effectiveness within, or across these combinations are difficult because it is not always possible to determine whether successful eradication or population control is a result of a single intervention or the cumulative effects of two or more interventions within that combination. This is especially true if applications are conducted simultaneously or in close temporal proximity of each other, and/or if limited details are provided to determine otherwise. Nonetheless, some general patterns can be seen from the studies. See Table S16 for summary characteristics and results of studies implementing various combinations of removal measures for population control or eradication of a non-native fish species

Although limited in number, there are studies showing effective eradication with lake dewatering in conjunction with chemical treatment. Successful eradication of non-native fish using the combination of dewatering of lakes/ponds followed shortly after by one chemical application of lime was reported in two studies (David 2003; Britton et al. 2008). For both studies, post-monitoring was reportedly conducted shortly after liming had been implemented. In a third study, Inland Fisheries Service (2005) reported the ineffectiveness of two predatory fish species (rainbow and brown trout) to eradicate Eastern mosquitofish in a reservoir in Tasmania. Although very little details are provided – resulting in a very low study validity assessment–, after the biological control attempt failed, the reservoir was subsequently dewatered and treated with a chemical (the type unstated) that was reported to be successful in eradicating the non-native population.

Mixed results have been reported for the effectiveness of stocking predatory fish for population control following unsuccessful eradication attempts using rotenone. Ward et al. (2008) evaluated the effectiveness of utilizing Bear Lake cutthroat trout (*Oncorhynchus clarkii utah*) to control Utah chub (*Gila atraria*) populations in a reservoir in Utah, USA, and over a 16-year period, predacious cutthroat trout were effective in controlling the chub population. Conversely, Michaels (2011) found that a large piscivore population, primarily largemouth bass (*Micropterus salmoides*), were ineffective in controlling common carp numbers in Illinois, USA. Both studies were classified as very low study validity as a result of deficient BA study designs.

Studies implementing a combination of physical and harvest regime measures also had mixed results for removal effectiveness. In all three cases, timing of applications for the different treatments overlapped. Earle et al. (2009) reported decreased abundance of brook trout after 11 years of selective harvest by anglers and electrofishing treatments. Using these same treatments, Evangelista et al. (2015) found that removal effort did not affect the total abundance of non-native North American pumpkinseed (*Lepomis gibbosus*) in France. Furthermore, an intensive study in Miramichi Lake, New Brunswick, Canada found that a combination of multiple physical removal measures and harvesting reduced the size of a smallmouth bass population (*Micropterus dolomieu*), but complete eradication was not achieved (DFO 2013).

The most frequent combination of removal measures included physical and chemical treatments to eradicate a non-native fish species (50% of the combination data set). Eradication was reported effective in 60% of these cases. Often physical removal measure(s) were used prior to chemical treatment(s) to minimize injury or mortality to native species present in the study waterbody, and/or remove as many non-natives as possible (e.g., Lintermans and Rutzou 1990; Lintermans and Bourne 2011); most of these attempted eradications were successful (but see Lintermans and Rutzou (1990) which reported eradications in some but not all ponds due to dense submerged weed beds and fringing emergent vegetation preventing mixing of rotenone). Buktenica et al. (2013), for example, reported a successful eradication of brook trout from Sun Creek, Oregon, USA, after 14 years of using electrofishing in the smaller headwaters of the creek, and the combination of electrofishing and antimycin treatments (5 applications between 1992-2005) in the larger downstream reaches. The use of trap-net electrofishing (i.e., custom-designed net constructed of 0.95-cm nylon mesh including two wings directing fish, herded by backpack electrofishers, through a fyke tunnel into a net bag) was reportedly very effective for removing brook trout and salvaging the native bull trout (*Salvelinus confluentus*) prior to chemical treatments (Buktenica et al. 2013). In another situation, chemical treatment with rotenone was applied first to Elk Creek, Yellowstone National Park, USA – a water system devoid of any native fish – and was followed by electrofishing (Ertel et al. 2017). Both treatments were applied once a year for three years resulting in the successful eradication of brook trout. Only one study reported an ineffective eradication attempt using the combination of physical and chemical measures. In a rapid response to round goby (*Neogobius melanostomus*) in Pefferlaw Brook, Ontario, Canada, Dimond et al. (2010) reported a failed attempt at eradication after using a single treatment of rotenone. Because an additional treatment of rotenone was not possible because the permit was limited to a single application, monitoring and removal intensified through the use of passive trapping, seining, electrofishing and angling; however, their attempts at eradication were unsuccessful and efforts then shifted to monitoring the spread of the non-native (Dimond et al. 2010).

Lastly, combinations involving physical and environmental measures have shown mixed results. Beatty and Morgan (2017) reported complete eradication of European perch from a reservoir in Western Australia using a combination of gillnetting and seining, and reservoir dewatering. In a different reservoir in Western Australia, however, Molony et al. (2005) reported unsuccessful eradication but effective reduction in abundance of European perch using a combination of gillnetting to reduce abundance of perch prior to dewatering, followed by a concussive technique using emulsion explosives.

Discussion

Implications for Management

Here, we present what we believe to be the first comprehensive review that systematically evaluates the quality and quantity of the existing literature base on the topic of the effectiveness of different non-native fish eradication and control methods. Although much of the evidence is based on poorly documented studies with inadequate experimental designs, and therefore considerable caution is warranted, our review nevertheless highlights some general points of consideration for management agencies and researchers.

First, when the goal of a management study is non-native fish eradication, chemical treatments had relatively high success rates (antimycin 75%; rotenone 89%)

compared to other interventions applied. Rotenone, in particular, was more commonly and widely applied globally than any other intervention measure for eradication, and often only required one application (Table S9). Study evaluations of electrofishing and passive removal measures showed successful eradication is possible (58% each respectively); however, intensive effort is often required with multiple treatments over a number of years (Table S10 and S11). Furthermore, effectiveness of electrofishing studies may be improved by having explicitly stated management objectives with study designs developed with those specific target objectives in mind. Although various combinations of removal measures in an attempt to eradicate a non-native fish have been used, many of these combinations have been applied in relatively few studies. The most effective combination with the most available data is the combination of physical and chemical measures (effective in 6 of 10 data sets; Table S16).

Second, when the goal of a management project is to control non-native fish population size, the effectiveness of different removal measures was quite variable with limited identifiable reasons for such variation. Of the studies with sufficient information, electrofishing had the highest success for population size control (56% of data sets); however, no discernible patterns could be found to explain variation in population control effectiveness (Table S12). Relatively few studies have been conducted on single passive and active netting measures, limiting adequate comparisons of effectiveness. Studies using multiple physical removal measures for population control were widely conducted across locales and waterbody types, and targeted a variety of non-native fish species; however, results showed a relatively low success rate (32% of data sets).

Finally, other removal techniques besides physical and chemical measures have been used in attempt to remove non-native fish from freshwater ecosystems, but they were comparatively under-represented in the available literature base. These include, – either alone or in combination with other techniques – biological control, harvest regimes, or water-level management measures.

Implications for Research

We believe one of the most important implications for researchers (and managers) is that many previously conducted projects have likely been undocumented. This failure to document and/or share knowledge on past efforts has undoubtedly come at a cost of lost learning opportunities, and wasted resources across jurisdictions. It became apparent through discussions with our advisory team and public engagement that much of the transfer of knowledge happens through informal discussion between networks of colleagues. Transfer of knowledge through informal networks is most certainly of value and should absolutely continue; however, knowledge transfer would be enhanced if the information is disseminated in a manner that ensures it will be permanently archived (in accessible formats) and more broadly distributed to those who require the information.

Failure to document and/or share knowledge on past efforts is not unique to our review topic (e.g., Davis et al. 2008; Ramstead et al. 2012; Lintermans 2013), and further underscores the need to make such information broadly available. One approach that might be of benefit is the use of journals that encourage submission of papers that document the outcomes of management practice (or field interventions) such as case study reports (e.g., Journal of Fish and Wildlife Management, Restoration Ecology, Environmental Management). Another approach could include forming collaborations between practitioners and scientists from universities, government agencies, or other organizations that may have more time and resources to help disseminate the information (Ramstead et al. 2012).

Our review highlights that there is still considerable room for improvement in our evaluations of non-native fish removal methods. The current evidence base is dominated by poorly documented studies with inadequate experimental designs; an observation that has been noted in previous reviews on this topic (Meronek et al. 1996; Corfield et al. 2007; Ayres and Clunie 2010). This may, in large part, be a result of the general approach taken with non-native fish management which is based on site-specific problem solving, and as such, relatively few studies incorporate replicated and controlled investigations with rigorous, long-term quantitative monitoring. Because of time and resource constraints, an adaptive management approach is often implemented, whereby the performance metric becomes the reduction in non-native fish abundance. As Corfield et al. (2007) noted, however, this approach is limited because measures of fish population size or the response of impacted species/communities are rarely used, and the level of control necessary to achieve desired goals remains unknown.

We also acknowledge there can be operational realities that are not always conducive to conducting robust research projects (e.g., repeated visits to isolated study locations, finding suitable analogous controls in close proximity within a study area), or ethical issues that might prevent activities that are harmful or inappropriate for species conservation (e.g., monitoring control sites where non-native fish are known to be present and possibly threatening native populations and not applying a removal measure).

Nevertheless, to improve our knowledge on when, where, and how non-native fish removal programs should be implemented, we need to modify our approach to evaluating the effectiveness of removal measures. In this regard, we provide a number of recommendations for future studies (see Table A2). Overall, explicitly stated objectives, better data reporting, study designs that (when possible and appropriate) incorporate experimentation into the process, use of quantitative outcome measures, and long-term assessments of removal methods are recommended. However, incorporating such recommendations will require greater funding from management agencies.

There are a number of knowledge gaps on the effectiveness of non-native fish removal methods that deserve further study. First, while previous studies have underscored variables that can affect the success of different removal measures [e.g., habitat complexity, physical water properties, and species-specific factors (e.g., Kolar et al. 2010; Britton et al. 2011*b*)], given the complexities of the natural environment, interactions between numerous variables makes determination of relationships between a single factor and outcome challenging. The lack of information reported on key environmental and methodological variables precluded an assessment of the effect of these sources of heterogeneity in a robust manner. Furthermore, even when reported, there was often not enough variation in values of the variables to determine whether they influenced the effectiveness of removal measures. For example, all electrofishing evaluations were conducted in lotic systems, mostly smaller creeks/streams, and in one relatively larger, but simple in morphology, river study. Furthermore, most single passive netting studies for non-native fish eradication have been conducted in relatively small [i.e., <90,000 m^2 (or 9 ha)], shallow [i.e., ≤11 m] lentic systems (Table S11). Second, there was an insufficient number of studies that investigated the use of biological control, harvest regime measures, or water-level management to draw meaningful conclusions on their effectiveness for non-native fish removal. To better inform management decisions, we need to improve research and data reporting for a broader range of removal measures. Third, the majority of the research has focused on a small number of fish species. As we continue to become globalized, the potential for invasion of non-native fish is real via one of the many invasion pathways. Being able to identify approaches that are most effective for a given species would be desirable. Similarly, there is little research on understanding the phenotypic characteristics of individuals within a population that fail to be eradicated. Do those individuals exhibit a particular behaviour (e.g., preference for deep water; see Sih et al. 2012) or have a particular physiology (e.g., metabolic rate or physiological capacity; see Lennox et al. 2015) that makes them less vulnerable to eradication or control? Knowing such information could provide insight into how to potentially adjust eradication and control efforts to better target all individuals in a given target population. These topics are at the fore of invasive species science and are being explored for sea lamprey in the context of pesticide resistance (Dunlop et al. 2017).

To facilitate the knowledge base required for developing more effective removal methods, we have the following recommendations for reporting of future studies. First, authors should provide raw data in an appendix or data archiving site. Outcome data should be reported for each year before and after implementation of a removal measure, and for each control and impact site *separately*. In other words, outcome data should not be combined across years and/or sites and authors should clearly distinguish before, during, and after intervention implementation periods, for each intervention method applied. Outcome data should also be recorded separately for each species or species group wherever possible. Second, authors should include information on: (i) study locations (e.g., waterbody type, waterbody area, depth, open or closed waterbody system, pH, temperature, discharge, plant density or coverage, canopy coverage, waterbody accessibility, and presence of containment measures prior to or during study), (ii) species-specific information (e.g., habitat preferences, time since non-native introduction or detection, vectors of introduction, and the extent that the population is established), (iii) the study design (e.g., outcome sampling method, outcome measure used, and duration of outcome sampling), (iv) interventions (e.g., type of removal measure(s), number of applications per intervention, number of different interventions, timing of application in relation to other applied interventions, if >1 intervention, method of application, and seasonality of intervention application), and (v) the overall project (e.g., level of intervention maintenance, if applicable, and project costs). If this information is already available in another published study, authors should direct readers to that information. If we are to further our understanding of removal measure effectiveness, it is essential we make all monitoring data available and provide comprehensive information on study locations, study design, intervention types and details of their application, and the outcomes used and how they were measured.

Review limitations

There were a number of limitations of this review. These limitations fall into three general (but interrelated) categories: (1) lack of high quality (low bias) studies; (2) lack of information reported on key environmental and methodological variables; (3) inaccessibility of data.

First, there was a paucity of studies designed to address our primary question in a robust, quantitative manner. Over 75% of removal projects were considered to have very low or low study validity, warranting considerable caution when interpreting removal measure effectiveness. The major causes for these classifications were due to: (1) low spatial/temporal replication (i.e., 47% of the included data sets had measurements for either one year before and one year after treatment for BA designs, or one control site and one impact site for CI designs); inadequate replication effectively limited effect size estimation for meta-analytical purposes for these data sets; (2) the use of a qualitative outcome measure for the comparator group and/or intervention group (i.e., 53% of data sets), limited our ability to use standard effect size estimates, and (3) relatively short duration of post-treatment monitoring (e.g., 54% of data sets did not conduct any ‘true’ post-treatment monitoring; of those that did, 49% only did so ≤1 year after the intervention was applied).

Second, missing information in relation to study methodology and environmental characteristics was a common issue. Key details were often not reported, or not easily identifiable, in relation to the date of intervention application when more than one type of intervention was applied, the number of applications, and accurate information on time since invasion. Similarly, information on various environmental variables related to the physical and chemical characteristics of the study location(s) were often not reported (e.g., depth, temperature, and whether the study waterbody was open or closed were reported in 38%, 20%, 54% of data sets, respectively). Inadequate data reporting severely limited our ability to address one of our main review questions: ‘What factors influence the effectiveness of each type of removal method and in what context is each technique most effective?’.

Lastly, we believe one of the greatest limitations of this review is that many previous studies have not been documented. Despite our best efforts to retrieve as much published and grey literature as possible, including discussions with our advisory team and public engagement over the course of this review, studies with limited, or a complete lack of documentation were common. It is difficult to speculate whether and how our results may be biased without inclusion of these studies; however, we did observe a higher ratio of effective to ineffective removal attempts from published articles compared to unpublished documents (6:1 and 3.6:1, respectively). If many ineffective removal attempts went unreported, our results may be biased by a tendency to report more frequently on effective studies. Although the “file drawer effect” may be partly responsible for this pattern, another potential explanation is that most removal studies are associated with management actions rather than research experiments. Furthermore, most management practitioners are not rewarded for publishing findings nor provided the support to do so.

In addition to possible publication bias, there were some geographical biases in the data. The majority of studies were from North American (62% of studies), in a particular USA (51% of studies), potentially limiting interpretation of review results to other geographic regions.

Conclusions

Our review highlights several key points of consideration for both the management of non-native fish and research on non-native fish eradication and population control methods. First, the evidence base was dominated by poorly documented studies with inadequate experimental designs. For proper evaluation and interpretation of the efficacy of non-native fish management techniques, programs should have explicitly stated objectives, and study designs that (when possible and appropriate) incorporate replicated and controlled investigations with rigorous, long-term quantitative monitoring (i.e., measures of fish population size both before and after treatment sampling rather than presence/absence data) (Table A2). Second, insufficient data reporting on important environmental and methodological variables severely limited our ability to make strong conclusions about the relationships between non-native fish abundance and different methods of eradication and population control, or the factors that influence the overall success rate of each type of method. To facilitate the knowledge base required for developing more effective removal methods, we need to improve data reporting by providing comprehensive information on study locations, study design, intervention types and details of their application, and the outcomes used and how they were measured. Lastly, our review would have been stronger if the results of more evaluations of removal measures had been made more widely available. Assessments of fish eradication and population control methods should be disseminated in a manner that ensures they will be permanently archived and more broadly accessed by those who require the information.

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Tables

Table 1. Critical appraisal tool for study validity assessment. Reviewers provided a rating of high, medium, low, or very low for each of the specific data quality features. BA: Before-After; CI: Control-Impact; BACI: Before-After-Control-Impact.

Category	Bias and generic data quality features	Specific data quality features	Design of assessed study	Score	Validity
1	Selection and performance bias: study design	Design (i.e., well-controlled)	BACI		High
			BA, CI, or Incomplete BACI		Medium
		Temporal repetition	Continuous Before–after (BA) time series (>1 replicates before and after)	25	
			Interrupted BA time series (>1 replicates before and after but not consecutive)	20	
			BA comparison (1 before, >1 after)	15	
			BA comparison (>1 before, 1 after)	12	
			BA comparison (1 before, 1 after)	10	
			Deficient BA comparison	2	
			No BA comparison	0	
		Spatial repetition	Site comparison/control-impact (CI) (>1 replicates control and impact)	25	
			Site comparison/control-impact (CI) (1 control, >1 impact)	15	
			Site comparison/control-impact (CI) (>1 control, 1 impact)	12	
			Site comparison/control-impact (CI) (1 control, 1 impact)	10	
			Deficient CI comparison (e.g. control-data from archives or not from the same period)	2	
			No CI comparison	0	
			Sum temporal and spatial repetition score =		
			>15/50		High
			12-15/50		Medium

			10/50	Low
			<10	very low
2	Assessment bias: measurement of outcome	Measured outcome	Quantitative	High
			Quantitative approximations (estimates)	Medium
			Semi-quantitative	Low
			Qualitative	Low
		Application coverage	Intervention was applied at an appropriate spatial and temporal scale relative to target species/waterbody	High
			Intervention was not applied at an appropriate spatial and temporal scale relative to target species/waterbody	Low
			Lacking sufficient information to judge	Low
3	Selection and Performance bias: baseline comparison	Habitat type	Intervention and comparator sites homogenous i.e. similar at baseline	High
			Intervention and comparator sites moderately comparable with respect to habitat characteristics	Medium
			Intervention and comparator sites hardly comparable due to different habitat	Low
			Lacking sufficient information to judge	Low
			N/A if BA design and before measurement taken immediately prior to eradication treatment	
		Other confounding environmental factors	Intervention and comparator sites homogenous	High
			Intervention and comparator sites moderately comparable with respect to confounding factors	Medium
			Intervention and comparator sites hardly comparable with respect to confounding factors	Low
			Lacking sufficient information to judge	Low
			N/A if BA design and before measurement taken immediately prior to eradication treatment	

Note: Deficient BA comparison: (1) before-data is not from the same site(s); (2) >5 years between before or after replicates; or (3) when there is only 1 before or after replicate and that replicate is >5 years either prior to or following intervention.

Table 2. Criteria for rating intervention(s) effectiveness aimed at eradication and/or population control of non-native fish and respective rating.

Criteria for rating intervention(s) effectiveness when the goal was:		**Effectiveness rating**
Eradication	**Population control**	
Evidence exists to conclude that the intervention(s) was successful in eradicating or likely eradicating a non-native fish by comparison of quantitative data from the comparator group and the intervention group, or stated by author that a successful eradication or likely eradication had occurred.	Evidence exists to conclude that the intervention(s) was successful in reducing non-native fish population size (e.g., abundance, density, biomass) by comparison of quantitative data from the comparator group and the intervention group, or stated by author that a successful reduction of non-native fish population size had occurred.	Effective
Evidence exists to conclude that the intervention(s) was successful in eradicating or likely eradicating a non-native fish by comparison of quantitative data, or stated by authors that a successful eradication or likely eradication had occurred but: (1) only in some, and not all treated waterbodies; (2) a non-native was known (or thought) to be re-introduced illegally after treatment, or (3) the project was still on-going.	Evidence exists to conclude that the intervention(s) was successful in reducing non-native fish population size (e.g., abundance, density, biomass) by comparison of quantitative data from the comparator group and the intervention group, or stated by author that a successful reduction of non-native fish population size had occurred but: (1) the project was still on-going; (2) only for a particular size class, suggesting subsequent removal treatments were needed to sustain low population size; (3) only in some, and not all treated waterbodies, or (4) the	Partly effective

	reduction in abundance was only initial, being followed by compensatory reproduction of mature fish that survived removal efforts or immigration and recruitment pulses soon after treatment.	
Evidence exists to conclude that the intervention(s) was not successful in eradicating a non-native fish by comparison of quantitative data from the comparator group and the intervention group, or stated by author that eradication had not occurred.	Evidence exists to conclude that the intervention(s) was not successful in reducing non-native fish population size (e.g., abundance, density, biomass) by comparison of quantitative data from the comparator group and the intervention group, or stated by author that a successful reduction of non-native fish population size had not occurred (i.e., there was either no change in population size or an increase in non-native fish population size with an applied intervention).	Ineffective

Table 3. Study validity of the included removal projects. BA: Before-After; CI: Control-Impact; BACI: Before-After-Control-Impact.

	no. of projects
Very low	
Temporal repetition: Deficient BA comparison	22
Low or unclear	
Study design: Sum temporal and spatial repetition score (=10/50)	28
Measurement of outcome: Semi-quantitative or qualitative	52
Application coverage: Intervention was not applied at an appropriate spatial and temporal scale relative to target species/waterbody	3
Application coverage: Lacking sufficient information to judge	33
Baseline comparison: Intervention and comparator sites hardly comparable with respect to confounding factors	1
Baseline comparison: Lacking information to judge for either	5
Medium	
Study design: Well-controlled design (e.g., BA, CI, or Incomplete BACI design)	21
Study design: Sum temporal and spatial repetition score (=12-15/50)	12
Measurement of outcome: Quantitative approximations	11
Baseline comparison: Intervention and comparator sites moderately comparable with respect to habitat	2
Baseline comparison: Intervention and comparator sites hardly comparable with respect to confounding factors	1

Note, the evidence for some projects has been assigned low or unclear, or medium study validity (i.e., high or medium susceptibility to bias) based on a combination of the data quality features.

Table 4. Number of cases of each intervention type within each intervention category in relation to the stated goal(s) of the study. Note, a data set could have >1 cases if >1 intervention types were applied, either from the same or different intervention category. Eradication/Population control: the stated goal was either eradication or population size control.

	Eradication	Population control	Eradication/ Population control	Total
Physical				
Passive netting	22	20	9	51
Active netting	3	8	1	12
Angling	1	3		4
Electrofishing	20	47	9	76
Unknown	1			1
Harvest				
Passive/Active netting		6		6
Angling	2	3	1	6
Chemical				
Rotenone	37	2	1	40
Antimycin	11			11
Other	6	2		8
Unknown	1			1
Biological				
Predator control	2	2	1	5
Environmental				
Dewatering	5	1	1	7
Other				
Explosives			1	1

Figure captions

Fig. 1. Results of literature search and study selection process showing the final number of studies included in the review synthesis. See Table S2 for details on exclusion categories.

Fig. 2. Year of publication of the 95 primary study sources.

Fig. 3. Percentage of the total number of removal projects within a given time period in relation to study validity. Number of removal projects per time period in brackets.

Fig. 4. Number of included data sets per country in relation to the stated goal(s) of the project. Eradication/control: the stated goal was either eradication or population size control.

Fig. 5. Percentage of data sets in relation to the number of main interventions applied for removal of non-native fish.

Fig. 6. The number of included data sets per intervention category used alone (i.e., no other main interventions were used) to either eradicate or control population size of a non-native fish species in relation to the effectiveness rating and study validity.

Appendix

Table A1. List of included primary study sources along with article ID. No. of data sets per study: an article could have (1) data for more than one non-native fish species; (2) evaluated different removal measure in different waterbodies.

Supplementary material

er-2018-0049.R1suppla

Text S1. Variances between search outlined in the review protocol and the systematic review.

Text S2. Description of database and search engine literature searches.

Text S3. List of specialist organization websites searched.

Text S4. Additional methods.

er-2018-0049.R1supplb

Table S1. List of relevant reviews hand searched to identify relevant articles that were not found using the search strategy.

Table S2. List of articles excluded on the basis of full-text assessment and reasons for exclusion.

Table S3. List of primary study sources for the included removal studies on the basis of full-text assessments, along with supplementary articles, that were selected for critical appraisal/data extraction.

er-2018-0049.R1supplc

Table S4. Study validity assessments.

er-2018-0049.R1suppld

Table S5. Data extraction sheet.

er-2018-0049.R1supple

Table S6. Number of data sets for each targeted non-native fish species for the North American countries in relation to the stated goal of the project.

Table S7. Number of data sets for each targeted non-native fish species in Europe, Africa, Australia and New Zealand in relation to the stated goal of the project.

Table S8. Summary characteristics and results of studies implementing antimycin alone for eradication of a non-native fish species.

Table S9. Summary characteristics and results of studies implementing rotenone alone for eradication of a non-native fish species.

Table S10. Summary characteristics and results of studies implementing electrofishing alone for eradication of a non-native fish species.

Table S11. Summary characteristics and results of studies implementing passive netting/trapping alone for eradication of a non-native fish species.

Table S12. Summary characteristics and results of studies implementing electrofishing alone for population control of a non-native fish species.

Table S13. Summary characteristics and results of studies implementing passive or active netting alone for population control of a non-native fish species.

Table S14. Summary characteristics and results of studies implementing combinations of physical removal measures for eradication of a non-native fish species.

Table S15. Summary characteristics and results of studies implementing combinations of physical removal measures for population size control of a non-native fish species.

Table S16. Summary characteristics and results of studies implementing various combinations of removal measures for population control (POPLN) or eradication (ERAD) of a non-native fish species.

<u>er-2018-0049.R1supplf</u>

Fig. S1. The availability of pre-, during- and post-removal outcome data from the included studies from Oceania, Africa, and Europe.

Fig. S2. The availability of pre-, during- and post-removal outcome data from the included North American studies.

Fig. S3. The availability of pre-, during- and post-eradication/control outcome data from included projects for more American studies (continued from Fig. S2).

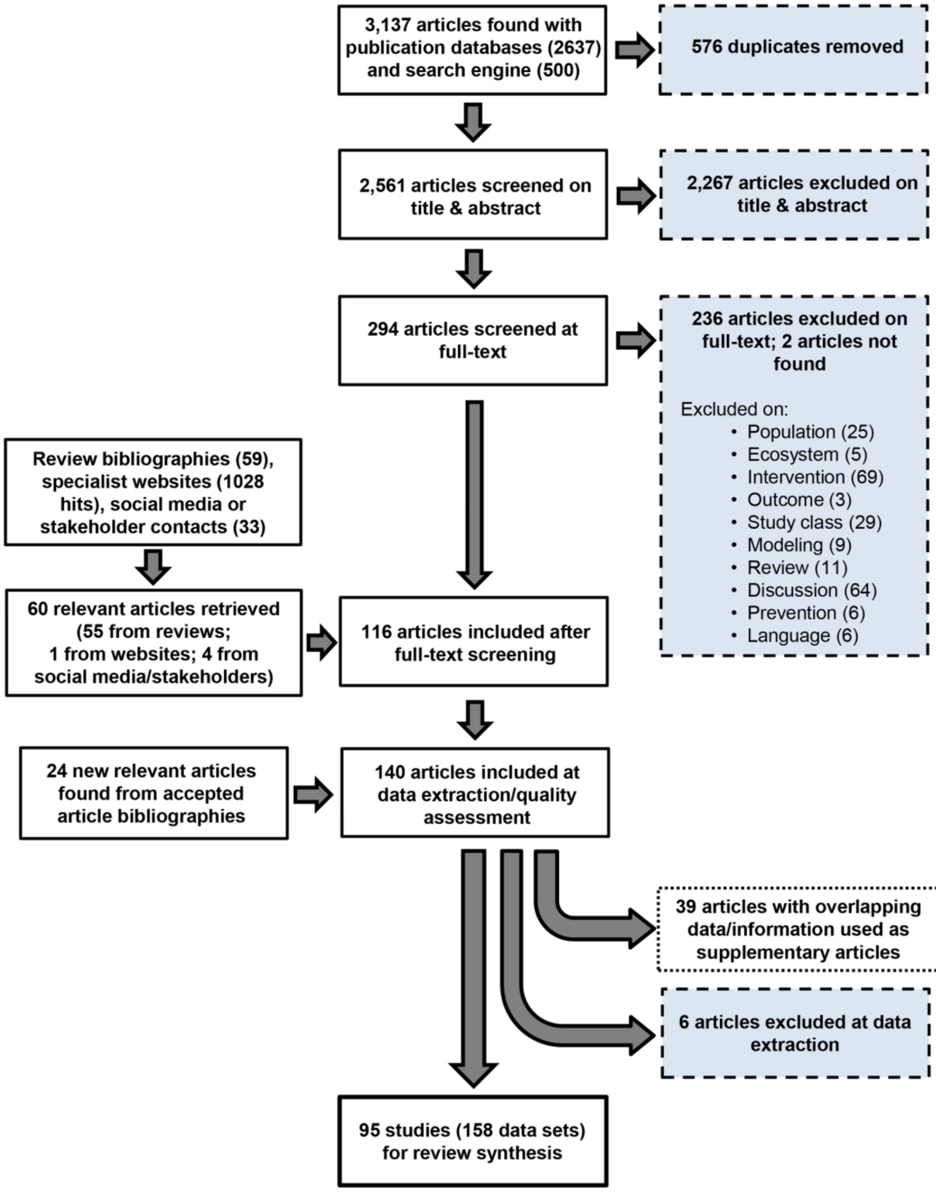

Fig. 1. Results of literature search and study selection process showing the final number of studies included in the review synthesis. See Table S2 for details on exclusion categories.

177x221mm (300 x 300 DPI)

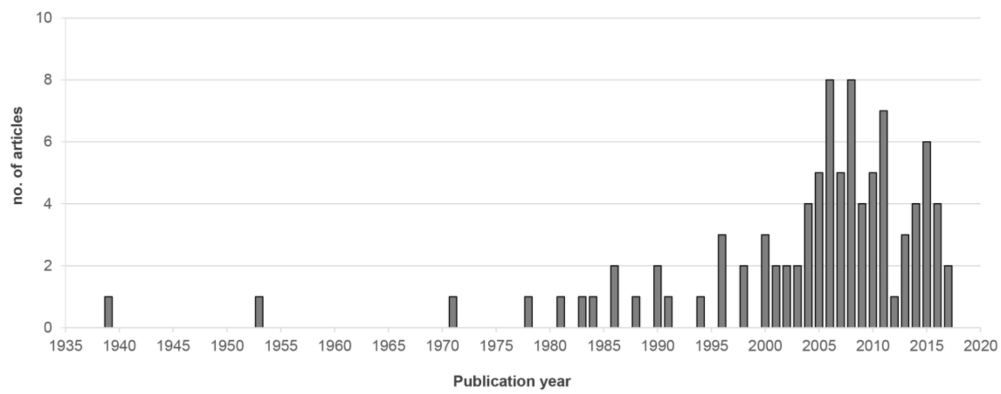

Fig. 2. Year of publication of the 95 primary study sources.

182x73mm (300 x 300 DPI)

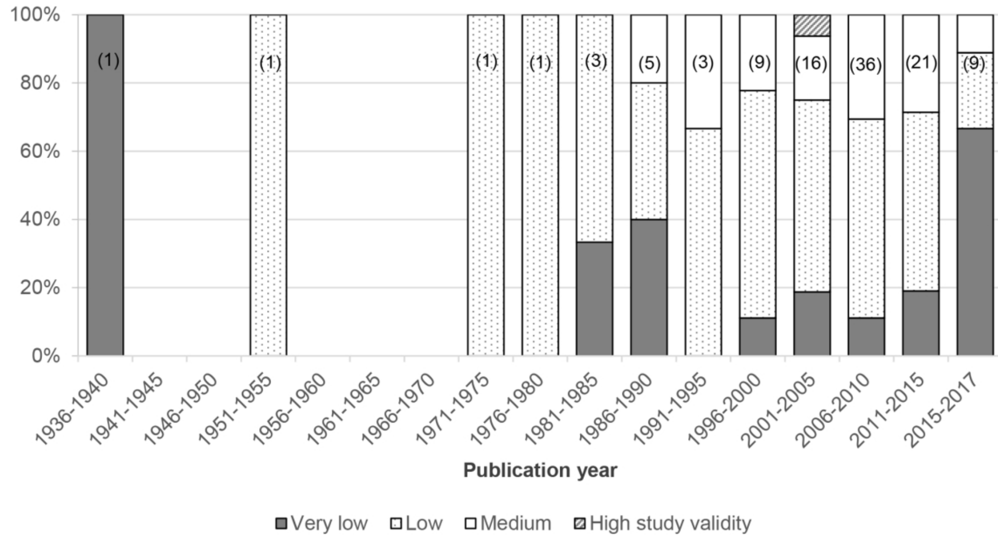

Fig. 3. Percentage of the total number of removal projects within a given time period in relation to study validity. Number of removal projects per time period in brackets.

86x47mm (600 x 600 DPI)

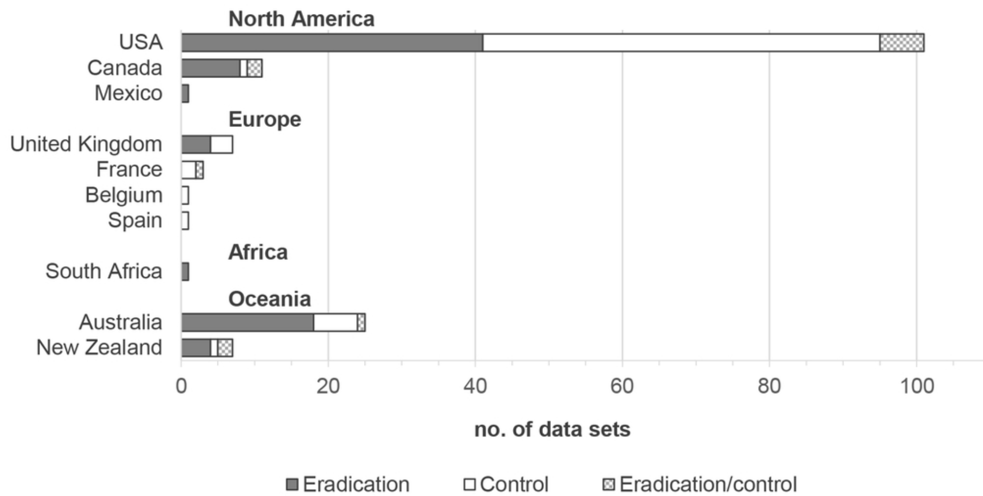

Fig. 4. Number of included data sets per country in relation to the stated goal(s) of the project. Eradication/control: the stated goal was either eradication or population size control.

86x43mm (300 x 300 DPI)

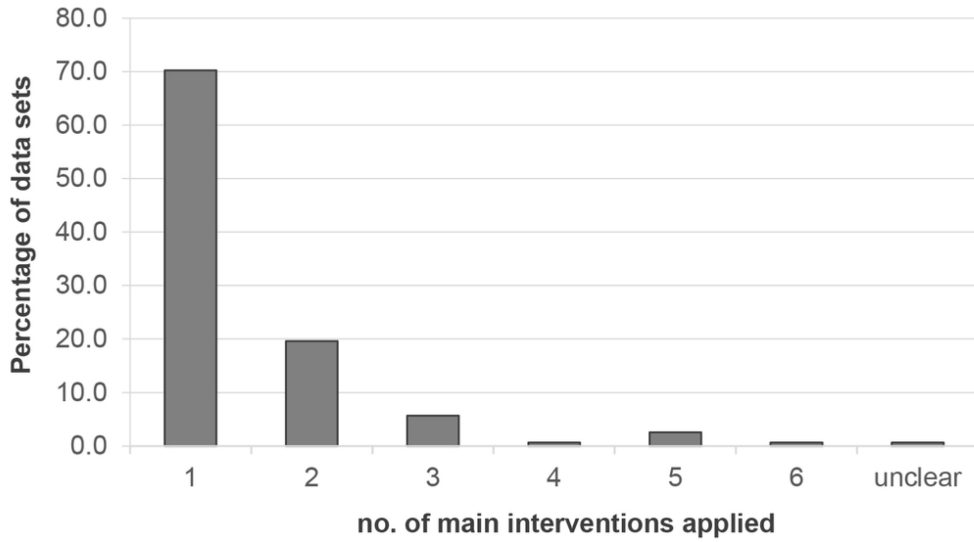

Fig. 5. Percentage of data sets in relation to the number of main interventions applied for removal of non-native fish.

86x47mm (300 x 300 DPI)

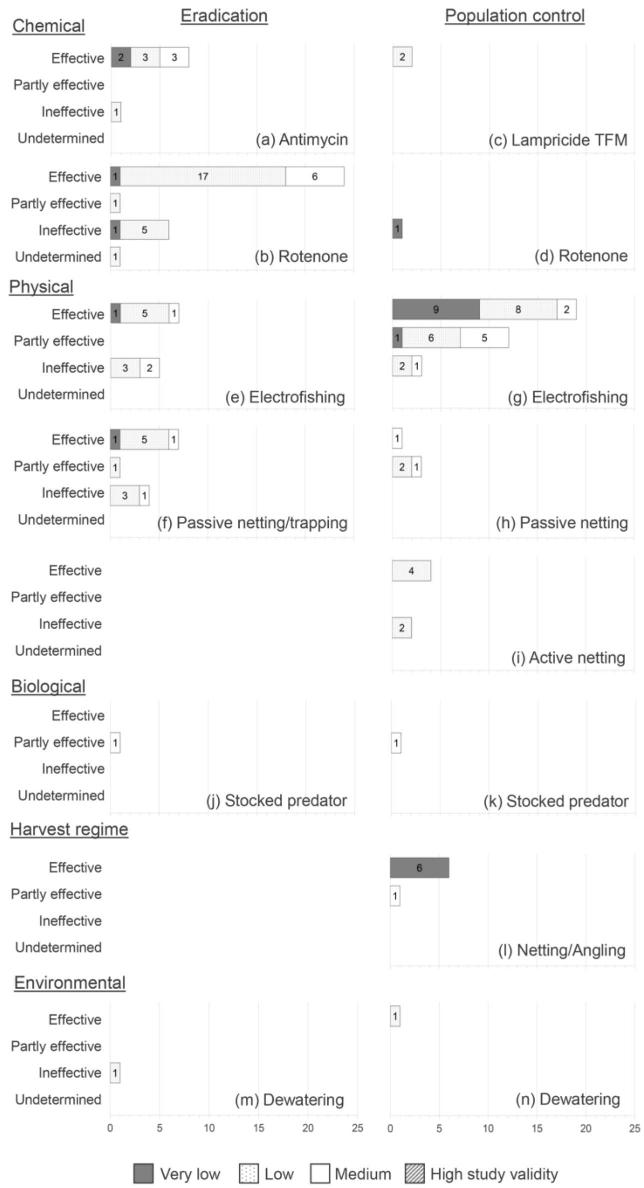

Fig. 6. The number of included data sets per intervention category used alone (i.e., no other main interventions were used) to either eradicate or control population size of a non-native fish species in relation to the effectiveness rating and study validity.

126x236mm (300 x 300 DPI)

Appendix

Table A1. List of included primary study sources along with article ID. No. of data sets per study: an article could have (1) data for more than one non-native fish species; (2) evaluated different removal measure in different waterbodies.

ID	Primary study source citation	No. of data sets per study
1	Lintermans, M., and Rutzou, T. 1990. Removal of feral fish from artificial ponds in the Australian National Botanic Gardens. Australian Capital Territory Parks and Conservation Service Wildlife Unit, Internal Report 90/12.	3
2	Lintermans, M., and Bourne, C. 2011. Keeping diseases and ferals out of Cotter Reservoir. Presentation to the Australian Society for Fish Biology annual conference, July 2011.	2
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Table A2. Recommendations for future study components to improve evaluations of non-native fish removal methods.

Project element	Description	Impact on assessment	Recommendations
Before data	often before data are not reported or a single before period > 5 years prior to intervention is reported	limits correct interpretation of intervention effectiveness	1. report all years for which before data were actually collected (including presence immediately prior to treatment); 2. collect continuous years of before data (when appropriate) or try avoid gaps in time longer than 5 years prior to intervention; 3. seek out existing monitoring data to supplement current projects
After data	often ≤1 year of post-treatment monitoring being conducted	limits correct interpretation of intervention effectiveness and recovery of the ecosystem	1. collect multiple years of after data; 2. strive for continuous years of data collection; 3. seek out collaborations with scientists from other agencies, or local universities for opportunities to extend post-treatment monitoring when resources are limited
Outcome measure	often a qualitative outcome measure was used for comparator and/or intervention group (e.g., the presence of a non-native before intervention and the numbers removed after)	precludes quantitative assessment of intervention effectiveness (i.e., standard effect size calculations)	1. use quantitative outcome measures for both assessment periods (e.g., relative abundance/density both before and after)
Management objective	lack of explicit management objective(s) for the study	outcomes cannot be adequately compared against objectives for correct interpretation of intervention effectiveness	1. develop a clear statement of management objective(s) at the beginning of the project; 2. develop study designs with those specific target objective(s) in mind (e.g., use appropriate temporal scale for monitoring assessment periods)
Control site(s)	lack of control sites being incorporated into study designs	without comparison of control sites with treatment sites, there is no way to know whether apparent effects of removal interventions are in fact due to the intervention and not a confounding variable	1. locate and include suitable analogous control sites in close proximity within a study area