Ecological Risk of Live Bait Fisheries: A New Angle on Selective Fishing

D. Andrew R. Drake

Great Lakes Laboratory for Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, 867 Lakeshore Rd., Burlington, ON, Canada L7R 4A6. E-mail: andrew.drake@utoronto.ca

Nicholas E. Mandrak

Great Lakes Laboratory for Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, Burlington, ON, Canada

ABSTRACT: *The use of live baitfish is a cultural norm in many jurisdictions across North America. Because baitfish are often harvested from mixed stocks in the wild, the potential for bycatch exists, leading to the inadvertent relocation of nontarget species via distribution networks and anglers; therefore, like many fisheries, core issues revolve around selective fishing. We assess selectivity of bait fisheries in Ontario, focusing on the prevalence of bycatch within the commercial supply chain and the propensity for nontarget species introductions by anglers. Selection for target stocks was strong; however, species assemblages in retail tanks and angler purchases included game, imperiled, invasive, and other nontarget species. The combination of bycatch, a large volume of angling trips, and risky angler behavior results in high probabilities of introducing the suite of nontarget species contained incidentally. Pathway approaches to management provide opportunities to increase selectivity, manage the risk of species introductions, and sustain the integrity of bait operations throughout North America.*

Riesgo ecológico de pesquerías con carnada: un nuevo enfoque de pesca selectiva

RESUMEN: *el uso de carnada viva es una norma cultural en varias jurisdicciones de Norte América. Debido a que los peces que se utilizan como carnada a veces son capturados junto con una mezcla de stocks silvestres, existe el potencial de que se vuelvan fauna de acompañamiento, lo que tiene como consecuencia que especies no objetivo sean reubicadas de forma inadvertida a través pescadores y de redes de distribución; por esta razón, como sucede en muchas pesquerías, el problema medular gira en torno a la pesca selectiva. En este trabajo se evalúa la selectividad de las pesquerías de carnada en Ontario, Canadá, haciendo énfasis en la prevalencia de la fauna de acompañamiento en la cadena productiva y en la propensión que existe por parte de los pescadores a reubicar especies no objetivo. La selectividad que existe para los stocks objetivo es intensa, sin embargo las asociaciones de peces que comercializan los pescadores incluyen especies de pesca deportiva, especies en peligro, especies invasivas y otras especies no objetivo. La combinación de fauna de acompañamiento, una enorme cantidad de viajes de pesca y un comportamiento riesgoso por parte de los pescadores, da como resultado una alta probabilidad de introducir una amplia gama de especies no objetivo que son contenidas incidentalmente. El manejo utilizando corredores, podría incrementar la selectividad, controlar la introducción de especies y mantener la integridad de las operaciones pesqueras con carnada a lo largo de Norte América.*

INTRODUCTION

Angling in freshwaters constitutes a substantial recreational pursuit throughout North America, with annual average participation in Canada and the United States of greater than 3.01 and 27.5 million resident anglers each year, respectively (U.S. Department of the Interior et al. 2011; Department of Fisheries and Oceans Canada [DFO] 2012). These individuals spend approximately 40.1 (Canada) and 455.9 (United States) million days fishing, with greater than C$2.9 billion and US$25.7 billion in fishing-related expenditures, annually (U.S. Department of the Interior et al. 2011; DFO 2012). Given high rates of participation throughout much of North America, angling has significant social, ecological, and economic implications. Angling with live baitfish is prominent, with the majority of live bait harvest, culture, and use by anglers occurring in freshwaters within certain eastern Canadian provinces and many Midwest and Southern states. The nature of baitfish activity varies across jurisdictions according to local regulations (Dunford 2012; Figure 1). Litvak and Mandrak (1993) conservatively estimated the value of the North American live baitfish industry at US$1 billion annually. The retail value of baitfish sales for Michigan waters alone was greater than US$5.7 million in 2012, with a minimum wholesale value of US$900,000 (Gary Whelan, Michigan DNR, Fisheries Division, personal communication), and retail sales from the Ontario industry were recently estimated at C$14 million (Ontario Ministry of Natural Resources [OMNR] and Bait Association of Ontario [BAO] 2006). Baitfish culture exists where feasible and profitable, with 257 farms or culture facilities operating within the United States in 2005 (U.S. Department of Agriculture 2005; Figure 1). Arkansas is the largest contributor of cultured baitfish, housing 51 farms with 2005 sale values of approximately US$20 million (U.S. Department of Agriculture 2005).

Commercial baitfish operations, such as harvesting from the wild, culturing, wholesaling, and retailing live bait, provide

Current address for D. Andrew R. Drake and Nicholas E. Mandrak: Department of Biological Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON, Canada M1C 1A4.

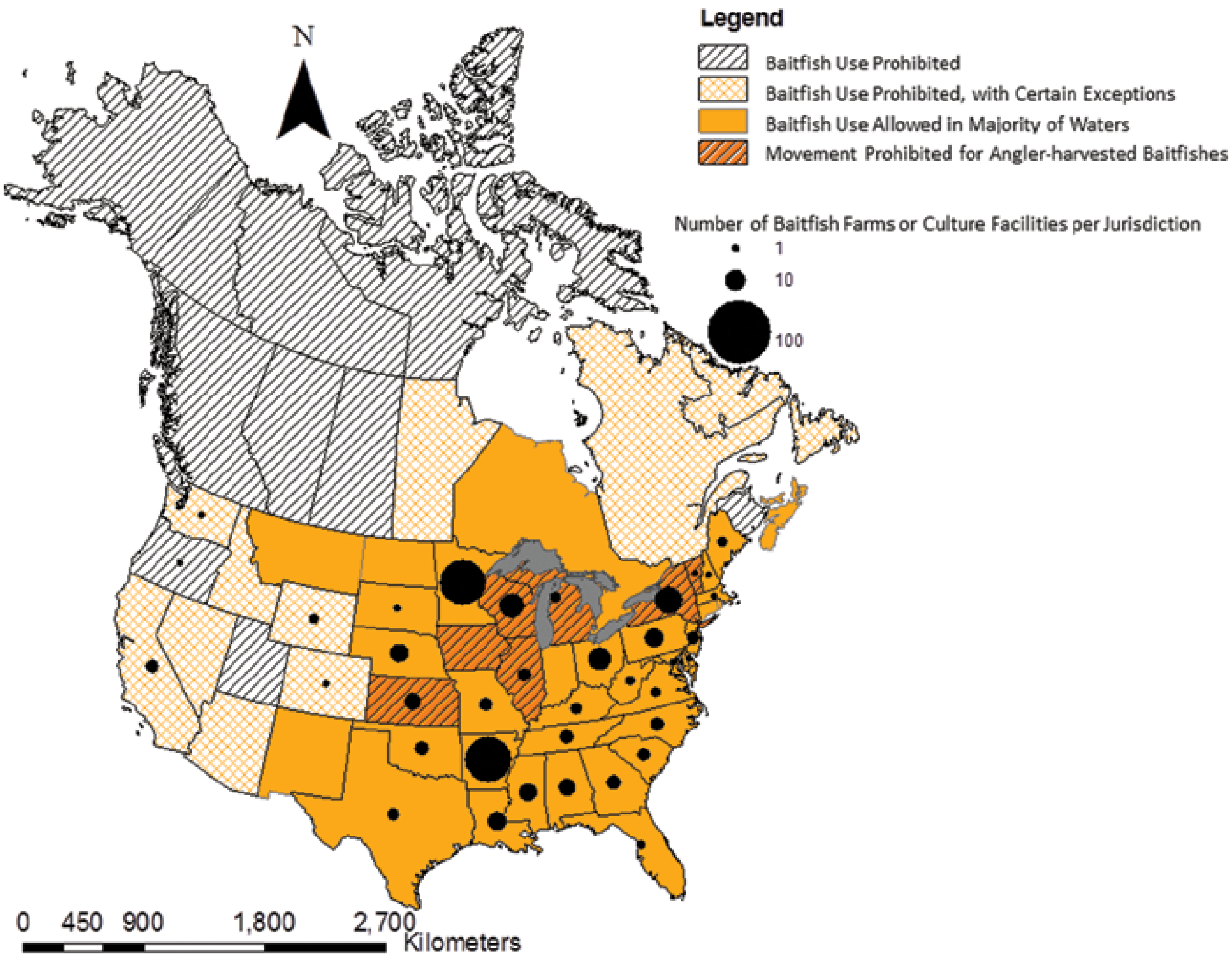


Figure 1. Characteristics of baitfish activity in North America, modified from a recent jurisdictional review (Dunford 2012).

a source of employment and revenue, and their live end-product provides an effective means of capturing game fishes with recreational methods. For many anglers across North America, live baitfish represent a relatively inexpensive source of bait, especially for individuals trapping their own fishes from the wild. Live baitfish are valued by anglers primarily because a live, natural bait provides scent, shape, size, vibration, and visual aspects familiar to game species. These attributes may increase angling effectiveness in a variety of recreational fishing scenarios, such as in turbid water, winter angling, or where inactive fishing techniques may be preferred, especially by new or occasional anglers.

Despite the many positive factors associated with the use of live baitfish for angling, concern exists surrounding the potential for biotic transfer between aquatic ecosystems due to baitfish use. Baitfish capture from the wild, and subsequent transport and release by anglers, may provide an effective pathway for the movement of fishes and their pathogens beyond biogeographic barriers (Litvak and Mandrak 1993; Ludwig and Leitch 1996; Goodwin et al. 2004; Figure 2), with ecological consequences dependent on the characteristics of transported species and recipient water bodies. Concerns surrounding the movement of fishes via baitfish pathways are consistent with a general increased awareness of human-mediated species introductions and their physical vectors (e.g., recreational boats: Rothlisberger et al. 2010; aquaria purchases: Strecker et al. 2011; commercial ships: Frazier et al. 2013) and the vulnerability of aquatic ecosystems to species invasions (Lodge et al. 1998; Sala et al. 2000).

Like many commercial and recreational fisheries, core issues within baitfish fisheries relate to the degree of selection (i.e., capturing target stocks while avoiding nontarget stocks); however, unlike most fisheries, bycatch issues are twofold. Typical bycatch issues, such as incidental capture leading to harm or mortality to nontarget stocks, are pertinent, but additional concerns about the live transfer of bycatch through each stage in the pathway (following inadequate sorting or culling by harvesters, retailers, and anglers; Figures 2A–2C) and movement and release by the angler (Figures 2D and 2E) complete the transfer of fishes from donor to recipient ecosystem. As with many commercial and recreational fisheries, selecting for target stocks is imperfect. Despite harvest practices oriented toward target species, wild harvest may inadvertently capture one or more nontarget species as bycatch, given the propensity for mixed

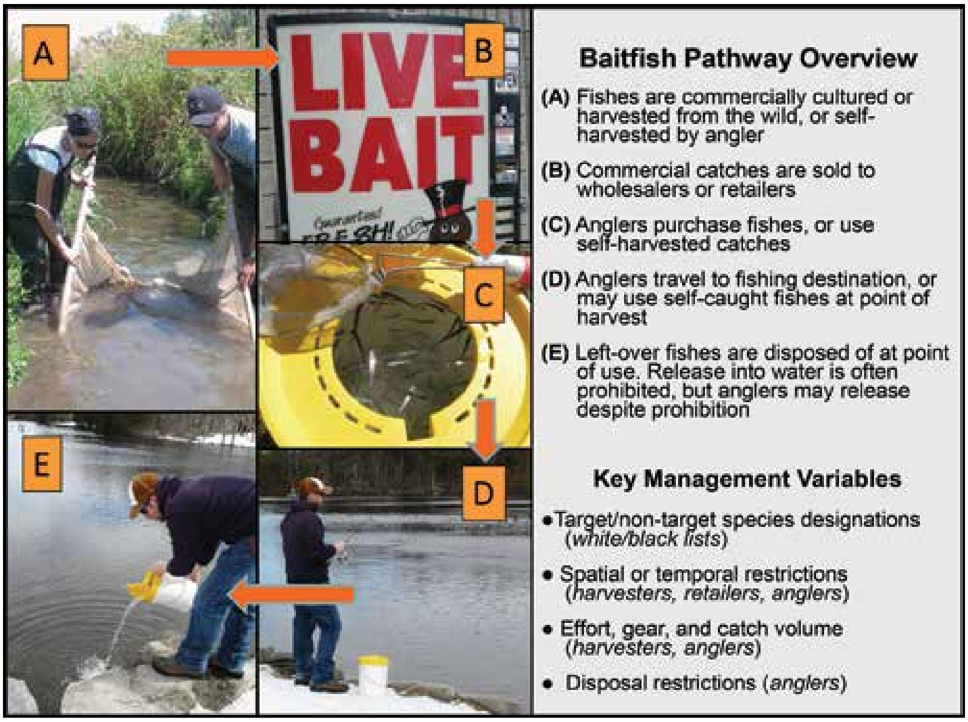


Figure 2. Diagram of baitfish pathways, which vary according to climate, biological resources, and local management.

stocks within harvest ecosystems (Drake and Mandrak 2014b) and difficulty of culling bycatch due to live, small-bodied, abundant target catches that obscure detection of nontarget species, which may also be small in size. Challenging species-level identification for many target and nontarget species, such as juvenile game species, contributes further to the difficulty of culling. Although physical species sorting will occur during and following harvest, undetected nontarget species may be inadvertently sold to baitfish retailers who, despite continued sorting, may inadvertently sell to anglers. Following purchase or self-harvest, nontarget species may remain undetected by anglers, who may transport species to the angling destination. Many jurisdictions prohibit angler release of leftover baitfish, but despite regulation, anglers may release their unwanted or leftover baitfish following travel to the destination waterbody, which may or may not contain the captive target or nontarget species. Release completes the pathway, with the transfer of fishes from donor to recipient ecosystems.

Current understanding of baitfish activity within North America is limited, especially as it relates to the potential for species bycatch and subsequent movement and release of captive species to the wild. This reduces capacity for science-based management decisions concerning the ecological risk of introducing key nontarget species. Recent research regarding the ecological impact of baitfish pathways has established baseline information about key species, their ecological characteristics and pathogens, and invasion potential within the pathway at broad scales (Goodwin et al. 2004; Kilian et al. 2012). To determine the risk of species introductions and guide pathway management toward reducing this risk, we summarize results of an assessment of the Ontario baitfish pathway, from points of commercial harvest and retail operations, through angler use and release, to estimate the incidence of bycatch and introduction of fishes beyond their current geographic range.

Model System—The Ontario Baitfish Pathway

The Ontario baitfish pathway involves a large network of harvesters, retailers, anglers, and destination water bodies (Table 1), providing a suitable system to study the degree of selective fishing and angler activities leading to the transport and introduction of fishes. Ontario's northern climate effectively precludes culturing, so the pathway relies upon wild harvest by commercial operators and self-harvest by anglers. Target species are small-bodied fishes from Catostomidae, Cottidae, Cyprinidae, Gasterosteidae, Percidae, Percopsidae, Salmonidae,

Table 1 . Summary statistics of the Ontario baitfish pathway and angling activities. Monetary values are given in Canadian dollars. Angler summaries are 2010 statistics (DFO 2012), and industry statistics are from 2005 (OMNR and BAO 2006).

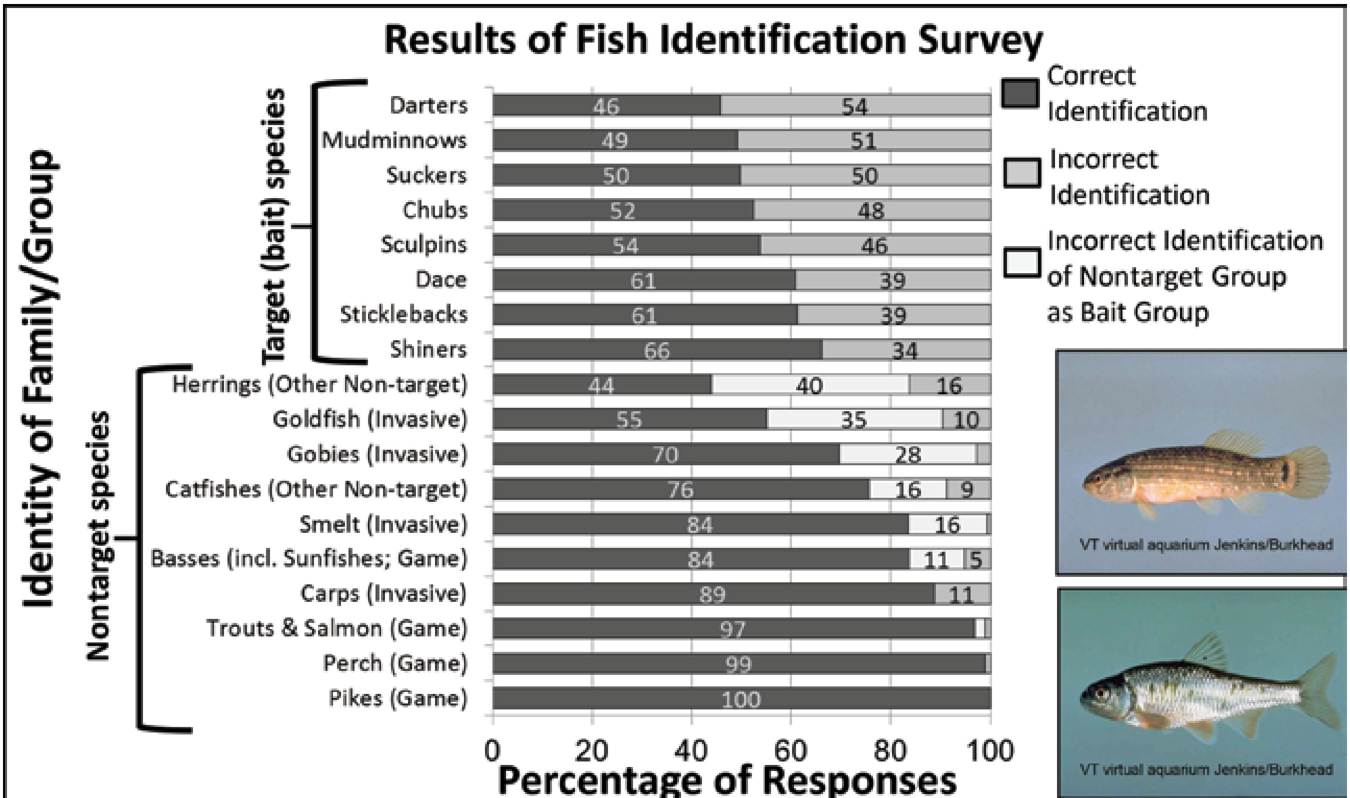
Ontario angler statistics (2010)	
Direct fishing-related expenditures	$912 million
Total resident and nonresident anglers	1.4 million
Total active resident anglers	924,549
Total angling days	16.9 million
Estimated resident angling events involving live baitfish	4.2 million[a]
Ontario baitfish industry (2005)	
Harvesters	670
Dealers/retailers	769
Number of fish harvested	≈100 million
Number of fish sold	≈49 million
Retail value of fish sold	$14 million

[a]Drake and Mandrak (2014a).

and Umbridae families, designated through a provincial white list of allowable species and harvested using live-capture gear (straight and bag seines, minnow traps). Recent estimates of commercial landings in Ontario indicated a yearly harvest of over 100 million fishes sold by several hundred retail dealers to supply substantial resident and nonresident angling activity (1.4 million total resident and nonresident anglers, 16.9 million total angling days, C$912 million in direct fishing-related expenditures; OMNR and BAO 2006; DFO 2012). Angling occurs within a landscape of >225,000 lakes, of which ca. 5% are greater than 1 km^2 in size (Cox 1978). Many of the large, accessible lakes support extensive live bait angling activity (Drake and Mandrak 2010; Hunt et al. 2011), as do numerous rivers throughout the province. Here, we focus primarily on ecological concerns associated with baitfish use through the commercial distribution network, as opposed to self-harvest by the angler. A paucity of data surrounds angler self-harvest, including capture locations, the degree and context of movement following self-harvest, and the extent of species sorting by anglers, especially as to the identification of baitfish and bycatch within personal catches. Preliminary results of a species identification survey collected from anglers who use live baitfish indicates limited identification skill for nongame species, including target baitfish and many nontarget species anticipated to be captured within personal catches as bycatch (Box 1).

Commercial Harvest: Selection of Fishes from Donor Ecosystems

Within Ontario, harvest occurs throughout much of the provincial landscape, including nearshore areas of the Laurentian Great Lakes, their tributaries, and many other inland water bodies (OMNR and BAO 2006). To quantify the potential for bycatch, we modeled baitfish harvest using fishery-independent data and a generic harvest strategy to address the following questions: (1) Which ecosystems exhibit greatest bycatch risk based on spatial cooccurrence between target and nontarget stocks at sites available for harvest? (2) What is the overall probability of capture for any nontarget stock? and (3) What is the relationship between bycatch and harvest effort? We focused on southern, speciose ecosystems (Great Lakes tributaries, hereafter "inland," and nearshore Lake Erie, hereafter "Lake Erie"; see Drake and Mandrak [2014b] for modeling details) due to extensive landings in these regions. To summarize the species contained within harvest ecosystems, we conducted hierarchical cluster analysis of species occurrences using a Jaccard resemblance measure (see Jackson et al. [2010] for details involving unweighted pair-group method with arithmetic averages and approximately unbiased estimates). Many target species cooccur with many nontarget species in the wild, including game, imperiled, and invasive nontarget stocks (Figure 3, harvest



Box 1. Angler fish identification skill is an overlooked component of live bait angling. Anglers incorrectly identifying game, imperiled, invasive, or other nontarget species as bait may unknowingly self-harvest species of concern and transport them beyond their range. Incorrect identification also decreases the ability of anglers to selectively remove nontarget species purchased incidentally as bycatch and may influence risk perception and disposal behavior for captive species. Results show fish identification accuracy based on a survey distributed to anglers who indicated angling with live baitfish (average response *n* = 159). Species were placed in general groups or families (e.g., catfishes) and anglers were required to correctly classify the group. Designations (e.g., game) were assigned based on the greatest number of species in a given category. Suckers were classified as target species given their popularity as bait, despite many nontarget species within the family. Shown are correct classifications (dark grey), incorrect classifications (medium grey), and, for nontarget groups, incorrect identification as groups dominated by bait species (light grey). Photos in the identification test were reproduced with permission from the Royal Ontario Museum, EFISH: The Virtual Aquarium of Virginia Tech, and the Wisconsin Fish Identification Database. Example photos of mudminnows and shiners are displayed.

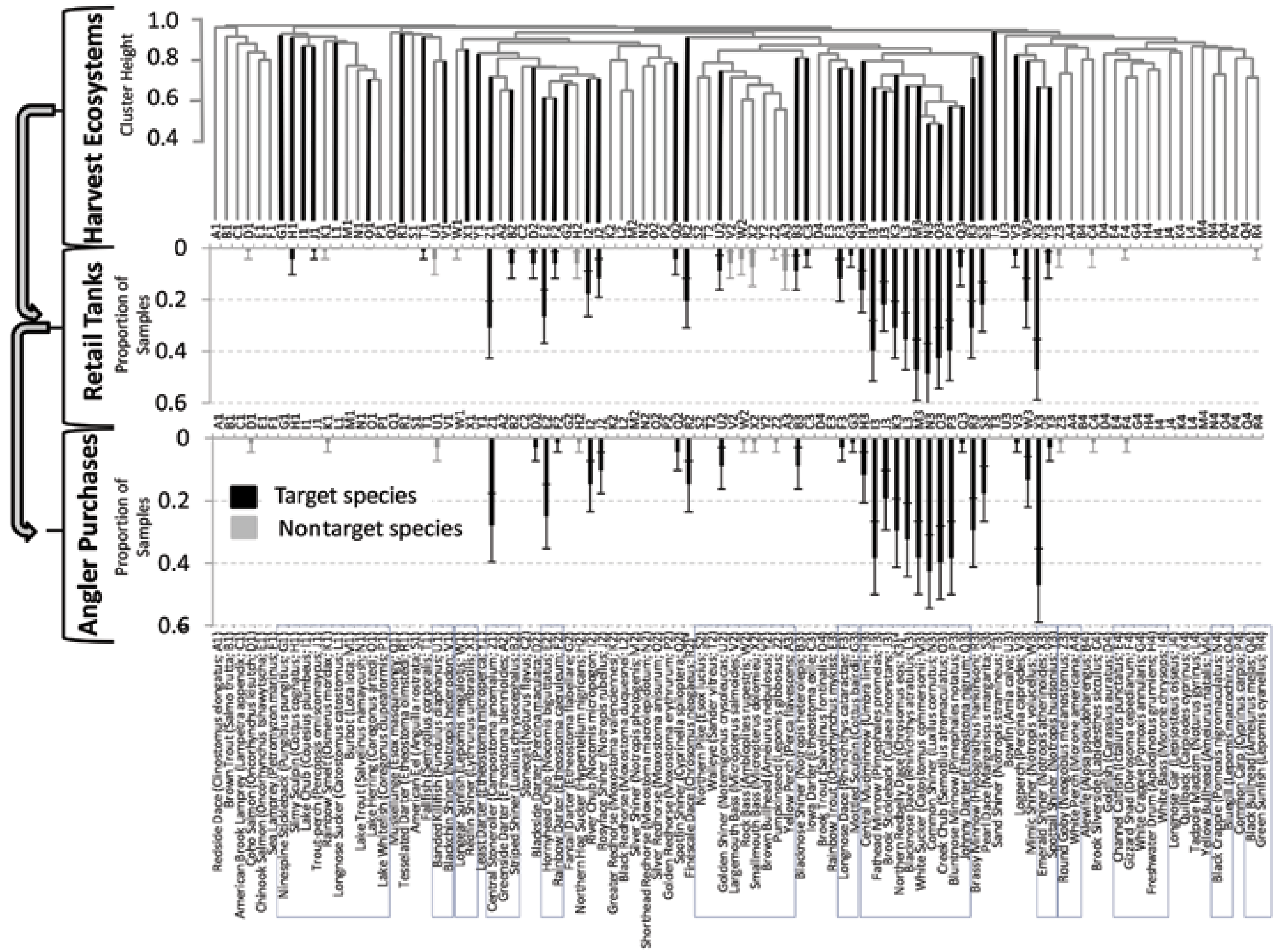


Figure 3. Target (black) and nontarget (grey) species within the Ontario baitfish pathway. The dendrogram within the harvest panel is based on fishery-independent species occurrence data for 6,970 sites accessible for harvest. Species occurring in less than 1% of localities were removed. Rectangles placed over species labels below the x-axis indicate frequently occurring species assemblages (approximately unbiased estimate ≥0.95 following 10,000 iterations). Also shown is the species composition for samples of retail tanks and angler purchases from the Ontario southern region, with y-axis values representing the proportion of samples containing each species and error bars representing the 95% bootstrap confidence limits. Note that River Redhorse, a nontarget species purchased as bycatch, is not included due to its rarity within harvest ecosystems.

ecosystems panel). In some cases, target and nontarget species coexist in frequently occurring assemblages (e.g., Golden Shiner *Notemigonus crysoleucas* with many game species). Based on these stock patterns and a generic harvest model, probabilities of capture for nontarget species associated with a single harvest event ranged from low (median $P_{\text{capture (Fourspine Stickleback | target spp.)}}$ = 0.000044; inland harvest) to high (median $P_{\text{capture (Brook Silverside | target spp.)}}$ = 0.3991; Lake Erie harvest) but, generally, gamefish stocks held the greatest probability of capture due to their frequent cooccurrence with target species and ease of capture with common gears (Drake and Mandrak 2014b). Many imperiled, invasive, and other nontarget species are also likely to be captured, should a large number of harvest events occur (Drake and Mandrak 2014b). Therefore, the underlying species composition of harvest ecosystems, the capture ability of the gear, and harvest effort are important factors influencing bycatch. The fate of species captured as bycatch varies based on individual harvest and sorting practices. Species captured as bycatch may be discovered and returned to the wild at point of harvest, removed from catches offsite, or remain undetected and inadvertently transferred to the retailer.

Retail Tanks and Angler Purchases: Incidental Transfer Following Harvest

Although the fate of bycatch captured by harvesters is uncertain (i.e., species may be returned to the wild if discovered in the net), the occurrence of nontarget species within retail tanks and angler purchases confirms imperfect culling and sorting practices following harvest from the wild. To assess the degree of selection following commercial harvest and quantify bycatch availability to the angler, we surveyed retail shops to determine the species composition of holding tanks and angler purchases of bait. Only southern facilities (i.e., those contained within the Ontario Ministry of Natural Resources southern region) were sampled due to the species-rich environments in southern Ontario that would provide the greatest potential estimate of bycatch in tanks and purchases. Fishes sold in this region originate primarily from the Lake Erie and inland harvests, providing a comparison of the identity and prevalence of harvested target and nontarget fishes with those sold by retailers. Of the total 181 southern retailers, 50 retailers were selected at random for sampling across two sample periods (August–October 2007, February 2008) to account for seasonality of species composition (i.e., inland fishes sold primarily during the summer, Emerald Shiner [*Notropis atherinoides*] sold primarily during fall, winter, and spring). Due to seasonal retail operations and variable baitfish supply, a total of 68 purchases occurred because some retailers were sampled only once. Purchasing occurred by requesting the legal maximum amount of baitfish allowed per angler from each retailer (120 baitfish in Ontario; see Drake and Mandrak [2014a] for sampling protocol). Individuals responsible for baitfish purchases did not identify themselves as researchers so that retailer behavior would not deviate from the norm, as in excessive sorting or counting. Following baitfish purchase, another member of the study team entered the retailer, identified the goals of the project, and asked the retailer whether they would allow sampling of the tank. In the event that a retailer would not allow sampling (frequent reasoning for refusal was related to fish harm), purchased fishes were used as a proxy for fishes contained in retail tanks. When permission was granted, tank sampling (and purchases) occurred from the tank containing the greatest abundance of fishes, which were captured with between 5 and 15 scoops of a small dip net throughout the extent of the tank. Because of the substantial abundance of fishes in most tanks, only species occurrences were documented.

The majority of fishes within retail tanks and angler purchases were target species; however, game, imperiled, invasive, and other nontarget species as bycatch were documented within tanks (15 nontarget species in total; 8 game, 1 imperiled, 2 invasive, 4 other nontarget species) and purchases (11 nontarget species total; 4 game, 1 imperiled, 2 invasive, and 4 other nontarget species; Table 2, Figure 3, retail tank and angler purchase panels). The proportion of angler purchases containing any nontarget species (0.147) experienced a 45% reduction from the proportion of retail tanks containing any nontarget species (0.324), potentially signifying culling by retailers prior to sale (Figure 4). For 7 of the 10 purchases containing nontarget species as bycatch, the purchase of a single nontarget individual occurred, whereas two purchases contained multiple nontarget individuals of different species, and another contained multiple nontarget individuals of the same species (Table 2). Notable species purchased as bycatch were imperiled River Redhorse (*Moxostoma carinatum*), invasive Round Goby (*Neogobius melanostomus*), and invasive Rainbow Smelt (*Osmerus mordax*; Figures 3, 4, Table 2). Only 0.195% of total individual fishes purchased were nontarget species; therefore, bycatch occurs somewhat frequently in angler bait purchases but often as the occurrence of only one or a few nontarget individuals.

Results indicate generally strong directional selection for target stocks. Most nontarget species within tanks and purchases were those predicted to be frequently captured as bycatch due to their prevalence in harvest areas and ease of capture with common fishery gears. However, certain species prevalent within harvest ecosystems were absent within tanks and purchases (e.g., Alewife *Alosa pseudoharengus*, Common Carp *Cyprinus carpio*, White Perch *Morone americana*; Figure 3), indicating the success of culling by harvesters and retailers or that harvesters avoid specific sites or seasons with high bycatch potential. Some species, such as Yellow Perch (*Perca flavescens*) and Largemouth Bass (*Micropterus salmoides*), were found only in tanks but not purchases, potentially indicating preferential culling for visually striking species. Rare captures as bycatch occur, such as River Redhorse and Coho Salmon (*Oncorhynchus kisutch*), presumably due to the high yearly volume of commercial catches (Table 1) where even the rarest species may be expected over a large number of harvest events that span diverse habitats and species assemblages. Harvest methods and culling, though imperfect, generally remove most nontarget species anticipated as bycatch.

Angler Activities

To determine the ecological implications of bycatch sold to the angler, we modeled how bycatch contained in bait purchases may lead to fish introductions in Ontario lakes. Anglers are critical pathway endpoints because they are highly mobile (Post et al. 2008; Drake and Mandrak 2010, 2014a; Hunt and Lester 2011) and represent the last control point before fish are potentially released to recipient ecosystems. We quantified angler activities, such as the purchase of baitfish, angler travel patterns, and the release of fishes contained in bait buckets, based on a large social survey (n = 1,393 respondents; see Drake and Mandrak [2010] for surveying details), and developed models to understand the transport and release of nontarget fishes by anglers.

Survey results indicated a large fraction of anglers choosing to fish with live baitfish ($P = 0.813$). Anglers indicated purchasing, self-harvesting, and releasing their fishes, with prevalence varying across regions (Table 3). Despite a long history of outreach programs and provincial fishery regulations prohibiting bait bucket release, survey responses indicated that a relatively large proportion of anglers ($P = 0.299$) continue to release unwanted or leftover baitfish, including anglers who release their purchased, as opposed to self-harvested, fishes. Drake (unpublished data) investigated the attitudes of anglers who release their bait. Although anglers indicated many possible reasons for bait release, such as the belief that release does not contribute to the spread of invasive fishes, the best predictive model of release behavior involved two joint variables: (1) releasing anglers indicated that bait release into water was convenient; and (2) releasing anglers also indicated that they believed that releasing leftover fishes provided a forage resource for game fish. This convenience and forage rationale existed for 70.5% of releasing anglers. Although warned about the ecological consequences of baitfish release by management agencies, anglers may also subconsciously believe their release behavior to be benign given their poor discriminative ability of invasive fishes

Table 2 . Pooled composition and abundance of fish purchased from bait retail facilities. Species are listed in decreasing order of prevalence per family; all names are according to Page et al. (2013). Target and nontarget designations refer to species legal or illegal for use as baitfish within Ontario based on Drake and Mandrak (2014b). To highlight the abundance and identity of nontarget species in an individual purchase, letters in brackets indicate each of the 10 purchases (A through J) in which nontarget species were purchased. For example, one of the purchases containing nontarget fish (A) was composed of two Rock Bass and one Smallmouth Bass. Another single purchase (B) contained a single Pumpkinseed, and a third purchase (C) contained a single Coho Salmon. On one occasion, a single purchase (D) contained four of the same nontarget species, and purchases (H) and (I) were both composed of single individuals of Banded Killifish.[a]

Target fishes	Total abundance
Family Cyprinidae	
Emerald Shiner (*Notropis atherinoides*)	10,333
Northern Redbelly Dace (*Chrosomus eos*)	1,055
Common Shiner (*Luxilus cornutus*)	1,002
Fathead Minnow (*Pimephales promelas*)	739
Blacknose Dace (*Rhinichthys atratulus*)	653
Creek Chub (*Semotilus atromaculatus*)	582
Bluntnose Minnow (*Pimephales notatus*)	477
Hornyhead Chub (*Nocomis biguttatus*)	227
Pearl Dace (*Margariscus margarita*)	196
Finescale Dace (*Chrosomus neogaeus*)	193
Mimic Shiner (*Notropis volucellus*)	133
Brassy Minnow (*Hybognathus hankinsoni*)	107
Golden Shiner (*Notemigonus crysoleucas*)	107
River Chub (*Nocomis micropogon*)	98
Central Stoneroller (*Campostoma anomalum*)	76
Spotfin Shiner (*Cyprinella spiloptera*)	47
Rosyface Shiner (*Notropis rubellus*)	41
Blacknose Shiner (*Notropis heterolepis*)	22
Spottail Shiner (*Notropis hudsonius*)	16
Longnose Dace (*Rhinichthys cataractae*)	2
Family Percidae	
Johnny Darter (*Etheostoma nigrum*)	8
Blackside Darter (*Percina maculata*)	3
Rainbow Darter (*Etheostoma caeruleum*)	1
Logperch (*Percina caprodes*)	1
Family Catostomidae	
White Sucker (*Catostomus commersonii*)	376
Family Gasterosteidae	
Brook Stickleback (*Culaea inconstans*)	338
Family Umbridae	
Central Mudminnow (*Umbra limi*)	19
Family Cottidae	
Mottled Sculpin (*Cottus bairdii*)	1

Nontarget Fishes	Total abundance
Game fishes	
Family Centrarchidae	
Rock Bass (*Ambloplites rupestris*)	2 (A)
Smallmouth Bass (*Micropterus dolomieu*)	1 (A)
Pumpkinseed (*Lepomis gibbosus*)	1 (B)
Family Salmonidae	
Coho Salmon (*Oncorhynchus kisutch*)	1 (C)
Invasive fishes	
Family Osmeridae	
Rainbow Smelt (*Osmerus mordax*)	4 (D)
Family Gobiidae	
Round Goby (*Neogobius melanostomus*)	1 (E)
Imperiled fishes	
Family Catostomidae	
River Redhorse (*Moxostoma carinatum*)	1 (F)
Other fishes	
Family Catostomidae	
Northern Hog Sucker (*Hypentelium nigricans*)[a]	18 (G)
Family Clupeidae	
Gizzard Shad (*Dorosoma cepedianum*)	1 (D)
Family Fundulidae	
Banded Killifish (*Fundulus diaphanus*)	2 (H [1], I[1])
Family Atherinidae	
Brook Silverside (*Labidesthes sicculus*)	1 (J)
Total fish purchased	16,886

[a] Since retail sampling, four species (Shorthead Redhorse, Silver Redhorse, Northern Hog Sucker, and Threespine Stickleback) have been listed as target species within the Ontario Fishing Regulations Summary (OMNR 2012). Note that Northern Hog Sucker were not listed as target species during initial sampling (August–September 2007) but were subsequently listed as target species. Northern Hog Sucker are included here as nontarget species, given that they were purchased during initial sampling.

(Box 1) or because angler opinions about the ecological consequences of fish invasions vary strongly (Drake and Mandrak 2014c).

To understand the ecological implications of bycatch in retail purchases, we modeled introduction risk of Round Goby, a key nontarget species given its invasion history in the Laurentian Great Lakes and impending inland range expansion associated with several vectors (e.g., canals, bait) and natural dispersal (Kerr et al. 2005; Mandrak and Cudmore 2010; Poos et al. 2010; see Drake and Mandrak [2014a] for model details). Models estimated 4.2 million yearly angling trips involving live baitfish that exhibited considerable spatial extent throughout the province, with angler effort positively correlated with lake size and sportfish richness (Drake and Mandrak 2010, 2014a). Based on our trip scenario of interest involving the purchase and release of Round Goby by anglers to lakes currently lacking the species, models indicated that most angling trips are benign. Most anglers and trips fail to introduce bycatch, due to the rarity of an angling trip occurring successively with the purchase (as opposed to self-harvest) of bait, the purchase of Round Goby as bycatch within target catches (as opposed to clean target catches), travel to an uninvaded (as opposed to invaded) lake, and release of captive nontarget species (benign trips, median $P = 0.99913$; Drake and Mandrak 2014a). Should the purchase of Round Goby as bycatch occur, most anglers fail to release

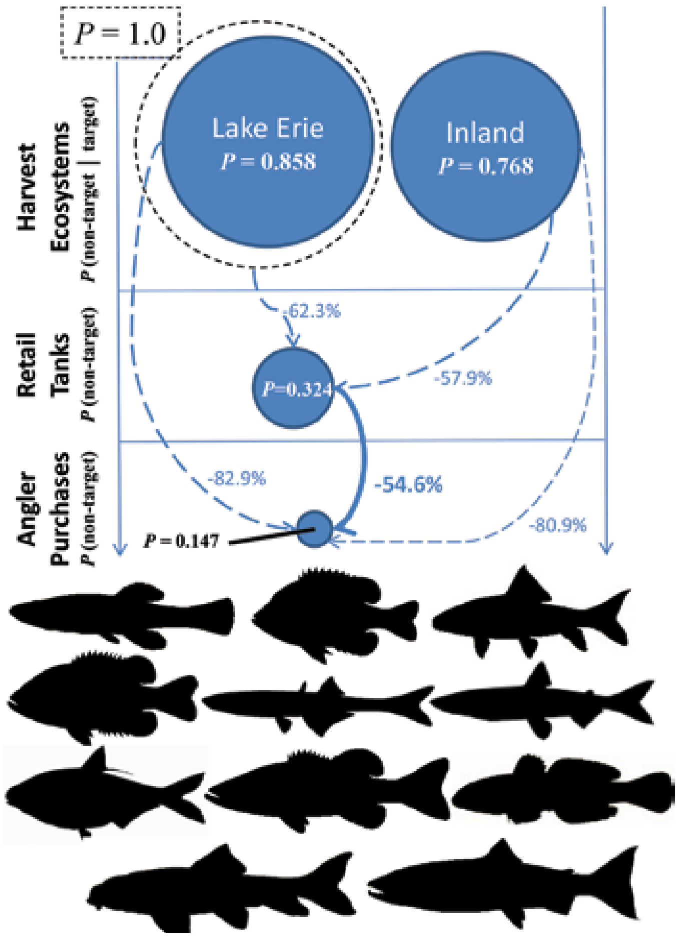


Figure 4. Proportion of harvest ecosystems, retail tanks, and angler purchases containing nontarget species following sampling within Ontario's baitfish pathway. Circles are scaled in size relative to 1.0 (dashed circle) and represent, from top left, the proportion of Lake Erie and Great Lakes tributary harvest sites containing nontarget species, given that they contain target species (i.e., $P_{nontarget \mid target}$); the proportion of retail tanks (middle) and angler purchases (bottom) containing nontarget species ($P_{nontarget}$). The solid arrow represents the reduction of nontarget species from retail tanks to angler purchases; dashed arrows indicate reductions from harvest ecosystems to tanks and purchases, albeit with uncertainty of the specific contribution of Lake Erie vs. inland sites toward the composition of nontarget species in tanks. Species outlines at the bottom are the 11 species purchased as bycatch: (top) Banded Killifish, Pumpkinseed, River Redhorse; (upper middle) Rock Bass, Brook Silverside, Rainbow Smelt; (lower middle) Gizzard Shad, Smallmouth Bass, Round Goby; (bottom) Northern Hog Sucker, Coho Salmon.

their captive species or, if they release, do so to lakes already containing the species, such as the Great Lakes. Substantially fewer trips are risky by successively purchasing Round Goby, traveling to an uninvaded lake, and releasing fishes; median $P = 0.00088$, or approximately 1 in 1,136 trips). Nonetheless, despite the low probability that an individual trip will lead to species introductions, the substantial yearly volume of angling activity will most likely result in 3,715 Round Goby introduced/year among 1,288 lakes currently lacking the species based on a baseline scenario (Drake and Mandrak 2014a). Similar mechanisms of introduction exist due to the high yearly volume of live bait trips for other species purchased as incidentally as bycatch, such as Smallmouth Bass (*Micropterus dolomieu*), Rock Bass (*Ambloplites rupestris*), and Rainbow Smelt, with each species exhibiting a high probability of being introduced during greater

Table 3 . Proportion of anglers indicating participation in certain behaviors within a given year, based on results of a social survey of anglers across Ontario (overall) and for each of Southwestern Ontario (SW, postal district N), the Greater Toronto Area (GTA, postal district L), Metropolitan Toronto (M, postal district M), Eastern Ontario (E, postal district K), and Northern Ontario (N, postal district P). The term "transport" refers to anglers indicating that they fish with self-harvested baitfish in waters other than where they were captured.

Behavior	Proportion of participating anglers (overall and per region)					
	Overall	SW	GTA	M	E	N
(A) Purchase but not self-harvest, given fish with live baitfish	0.813	0.792	0.804	0.774	0.749	0.922
(B) Purchase but not self-harvest, given fish with live baitfish	0.467	0.419	0.533	0.596	0.426	0.386
(C) Self-harvest but not purchase, given fish with live baitfish	0.021	0.023	0.022	0.000	0.017	0.028
(D) Self-harvest and purchase, given fish with live baitfish	0.511	0.558	0.444	0.404	0.557	0.586
(E) Release given purchase or self-harvest	0.299	0.359	0.324	0.326	0.261	0.225
(F) Release and transport given self-harvest	0.095	0.079	0.107	0.056	0.069	0.118

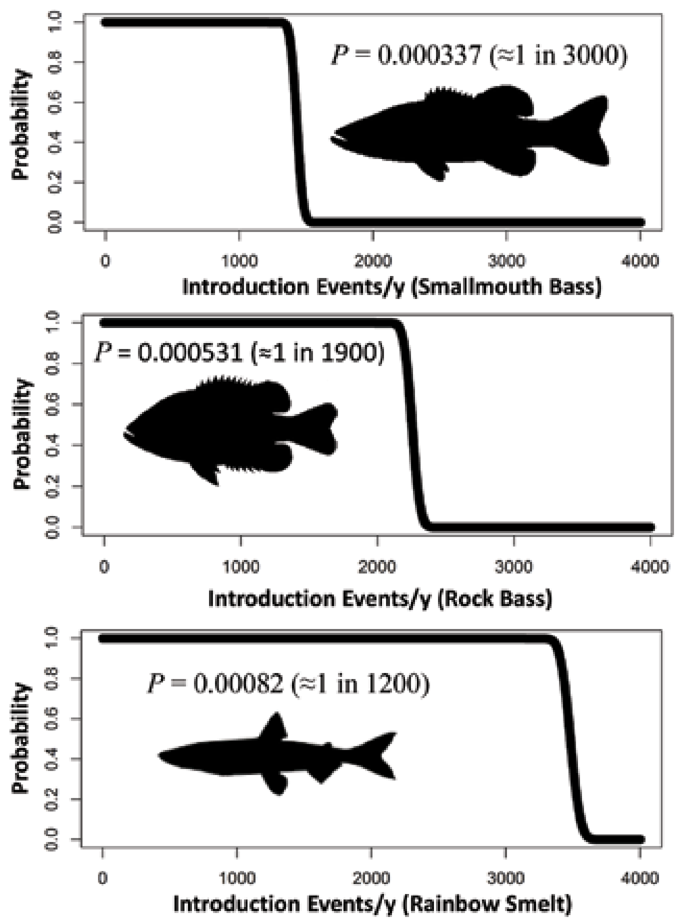


Figure 5. Probability (y-axis) of introducing Smallmouth Bass, Rock Bass, and Rainbow Smelt during at least *n* events/year (x-axis) to lakes currently lacking the species. Plots were derived as 1 − average cumulative probability density using the baseline Poisson agent-based model described in Drake and Mandrak (2014a). Probability values in inset represent the joint per trip probability of releasing purchased bycatch to a lake lacking the species.

than 1,000 events/y under the same baseline scenario (Figure 5; results obtained using model from Drake and Mandrak 2014a). Therefore, although species-specific bycatch rates in the Ontario live bait pathway are relatively low, and specific angling trips with the potential to release nontarget species are infrequent, the sheer volume of pathway activity (harvest events and live bait trips) strongly increases the probability that species are introduced beyond their native range within a given year (Drake and Mandrak 2014a). Nonnegligible species introduction risk exists, with a substantial number of fish introductions attributed to bycatch, fishing volume, and the many variations in live bait angler behavior (see Ludwig and Leitch [1996] for similar mechanisms and Box 2 for an assessment of bycatch introduction risk following self-harvest by anglers).

Species introductions are most likely at lakes exhibiting multiple risk factors: large physical size, diverse sportfish populations, and physical proximity to large angling populations and source populations of nontarget fishes, though most lakes are not immune to receiving bycatch given the many permutations of trip activity (Drake and Mandrak 2014a). Although the survival, establishment, and ecological impact of nontarget fishes following their introduction is extremely uncertain, many of the highest-risk lakes received a sufficient number of individuals each year to surpass demographic barriers to establishment for prominent fish invaders, such as the Round Goby (Vélez-Espino et al. 2010). Our models indicate that despite relatively low bycatch rates, the suite of nontarget species purchased incidentally will be introduced across the provincial landscape (Figure 5), as will those species documented in the future as bycatch within tanks and purchases.

Opportunities for Bycatch Reduction: Risk Management in the Face of Wild Harvest

Given our models and the incidence of nontarget fishes in retail tanks and angler purchases, what conclusions can be drawn about reducing bycatch and thus the ecological risk of species introductions attributed to the baitfish pathway? Logically, reducing bycatch during harvest from the wild will decrease the incidence of nontarget fishes throughout the commercial supply chain. This, in turn, will reduce the magnitude of species introductions following transport and release by anglers; however, bycatch reduction is no small task due to diverse species assemblages in many harvest ecosystems, gear effective at capturing many small fishes, challenging species identification, and scale of the fishery. To reduce the risks associated with the live transfer of bycatch, Ontario, as with many Midwestern states, has implemented the Aquatic Invasive Species-Hazard Analysis and Critical Control Point training program (Gunderson and Kinnunen 2001), which educates commercial harvesters about the risks of invasive fishes and pathogens and the need for effective species sorting. Despite the implementation of this program in Ontario during 2008, the incidence of nontarget fishes in purchased bait appears to have remained relatively constant (Drake, unpublished data), indicating either that (1) harvester training is ineffective and has no influence on bycatch rates; (2) due to its infancy, the program has yet to achieve its goals; or (3) irrespective of harvester training, existing bycatch rates are as low as possible within the current management regime. In other words, given the scale of the fishery and despite the best intentions of harvesters and the Aquatic Invasive Species-Hazard Analysis and Critical Control Point training program, a relatively low level of bycatch may be inevitable due to the nature of high-volume live-capture fisheries involving wild stocks. Harvesters and retailers are culling most nontarget species from catches, and despite these notable successes, low bycatch rates lead to species introductions with likely ecological consequences due to the sizable number of harvest and angling events each year.

If bycatch rates are currently as low as possible, achieving further bycatch reduction will require pathway management shifts beyond harvester training, such as overall reductions in harvest effort, which will reduce the probability of capture for widely distributed stocks like Yellow Perch, Rock Bass, or Smallmouth Bass or spatial harvest restrictions to address localized species of concern, such as Round Goby (Drake and Mandrak 2014b). Other harvest management initiatives, such as reexamination of allowable target species or temporal restrictions to reduce the probability of encountering congregations of nontarget fishes, may provide further opportunity to reduce risks. However, management shifts toward reducing bycatch will inevitably decrease the overall efficiency of harvest, so, like many fisheries, competing objectives exist. Alternatively, bycatch training programs targeting retailers as critical endpoints may provide important opportunities for removing bycatch within commercial supplies. Retailer programs should focus on enhancing the identification skill of retailers for target vs. nontarget species, in conjunction with installing designated receptacles at retail facilities for the placement of nontarget species following their discovery. Such an initiative acknowledges the incidence of bycatch within the fishery and may promote a proactive approach to species culling by retailers.

Despite the practical difficulties of implementing strategies to reduce risks, effectively reducing bycatch and the release by anglers will strongly influence the number of fish introduced each year (Drake and Mandrak 2014a). For example, the most likely number of Round Goby introduced would be zero following a 90% reduction of purchased bycatch, because the very low number of Round Goby sold either would not be released or would be released to popular angling lakes already containing the species, such as lakes Erie, Ontario, and Simcoe (Drake and Mandrak 2014a). Thus, risk-based bycatch thresholds exist. Targeting angler perceptions involving the convenience of bait release, such as with designated trash receptacles for leftover baitfish at high-risk lakes, will also reduce the number of nontarget fishes introduced. However, as with bycatch, some low-level of risky activity may persist with a subset of anglers continuing to release despite targeted management. Therefore, effective ecological risk reduction within Ontario's baitfish pathway is probably multifaceted by targeting both bycatch within the commercial supply chain and human dimensions relevant to risky angler behavior.

Box 2. Self-harvest of baitfish and bycatch by anglers

Self-harvest of fishes by anglers is an important component of live bait angling. As with commercial harvest, bycatch may occur during self-harvest. Anglers inadvertently transporting and releasing nontarget fishes beyond point of capture are an effective mechanism for the overland transport of a variety of small fishes. Using the binomial probability formula following Ludwig and Leitch (1996), P (K successes in N trials) = $\binom{n}{k} p^k(1-p)^{n-k}$, we present an estimate of the probability (P) that at least 100, 1,000, or 10,000 events/year will involve the transport and release of bycatch self-harvested by anglers, given p, the estimated per trip probability of bycatch, transport, and release; k, the number of successes (transport and release of bycatch/year); and n, the overall number of trials (angling events involving self-harvest; average 1,183,332 trips/year; Drake and Mandrak 2014c). Although the identity and prevalence of bycatch within self-harvested catches is unknown, most gear used by anglers (minnow traps, seines) capture a variety of target and nontarget fishes alike, and poor identification skill (Box 1) may influence culling decisions and effectiveness. Given the volume of trips involving self-harvest, even low per trip probabilities of contamination with nontarget fishes can lead to a high probability of at least 100 or 1,000 events/year in which nontarget fishes are released to where they were not harvested.

Hypothetical probability of contamination of self-harvested catches with nontarget fishes X	Per-trip probability of transport ∩ release | self-harvest* =	Per-trip probability (p) of bycatch ∩ transport ∩ release | self-harvest	Cumulative probability (P) that at least k events/year will involve the transport and release of bycatch self-harvested by anglers		
			100 events/year (k)	1000 events/year (k)	10000 events/year (k)
P = 0.001 (≈1 in 1000)	P = 0.095	P = 0.000095	P = 0.8704947	P = 0.0	P = 0.0
P = 0.002 (≈1 in 500)	P = 0.095	P = 0.00019	P = 1.0	P = 0.0	P = 0.0
P = 0.01 (≈1 in 100)	P = 0.095	P = 0.00095	P = 1.0	P = 0.9999137	P = 0.0
P = 0.025 (≈1 in 40)	P = 0.095	P = 0.002375	P = 1.0	P = 1.0	P = 0.0
P = 0.05 (≈1 in 20)	P = 0.095	P = 0.00475	P = 1.0	P = 1.0	P = 0.0
P = 0.1 (≈1 in 10)	P = 0.095	P = 0.0095	P = 1.0	P = 1.0	P = 1.0

*maximum estimate from Table 3 (behavior may occur for some, but not all, of self-harvested trips); we also assume that bycatch is not culled from catches when transport and release occurs
Photo credit: Fisheries and Oceans Canada.

IMPLICATIONS FOR MANAGEMENT: BAITFISH ACTIVITY ACROSS NORTH AMERICA

As with all recreational and commercial fisheries, management of baitfish across North America must focus on relevant ecological, social, and economic factors. We present an assessment of certain ecological factors and, like many before us (Litvak and Mandrak 1993; Ludwig and Leitch 1996; Lodge et al. 2000; Kerr et al. 2005; Keller et al. 2007; DiStefano et al. 2009; Kilian et al. 2012), draw attention to the potential for human-mediated species transport beyond biogeographic barriers. Ultimately, the ecological risk posed by bait pathways across North America is dependent on the nature of baitfish supply (e.g., wild harvest vs. culture), scale of associated commercial and recreational fisheries, and context of fish movement, with many scenarios of baitfish supply and angler use possible due to the complexity of jurisdictional regulations. In some jurisdictions, species-specific baitfish white lists and clear regulations pertaining to harvest and angling with live baitfish are sorely needed.

Fishery managers reviewing potential risks should focus on the potential for species bycatch and movement of fishes as key joint variables. For example, in jurisdictions such as Michigan, New York, and Wisconsin, regulations dictate that fishes self-harvested by the angler must be used at point of harvest (Dunford 2012). Though bycatch may occur during self-harvest, these regulations eliminate the overland movement of fishes (as one of the key joint variables), thus preventing biotic transfer for law-abiding anglers. In this context, the ecological consequences of angler bait release are also minimized. However, this approach limits the availability of angler-caught bait during ice-cover seasons, so supplementation with commercial catches is often warranted, with enforcement of personal vs. commercial fishes through a purchase receipt system. Alternatively, for many southern states (e.g., Kentucky, West Virginia), baitfish supply is supplemented through culture of common species such as Fathead Minnow (*Pimephales promelas*) and Golden Shiner. Culture strongly reduces potential for bycatch as the second key variable. However, as with pathways involving wild harvest, the volume and extent of the overland distribution network associated with many baitfish farms dictates that contamination with nontarget fishes or pathogens pose strong potential for rapid overland spread, should unwanted species fail to be discovered and contained (Goodwin et al. 2004). Pathogen and fish health certification programs undertaken by bait farmers, such as the Arkansas Certified Baitfish program (www.safebaitfish.org), are a positive step to reduce the likelihood of such events.

Where wild harvest exists, our results emphasize that bycatch can occur with important ecological implications, even within well-managed commercial supplies. Realistic opportunities for risk reduction exist, such as harvest management, bycatch control points at retailers, and outreach programs focusing on perceptions about bait release, though most risk management strategies cannot eliminate risk due to the scale of fisheries and stochasticity of relevant ecological and social processes. Therefore, determining the allowable spatial scale of fish movement between donor and recipient ecosystems, itself a risk tolerance decision, is warranted in the event that fishes and pathogens are transported and introduced despite risk reduction programs. Management agencies may pursue chain-of-custody systems for the commercial supply chain and anglers, so that the origin of baitfish can be determined readily during enforcement or in the event of discovery of an undesirable species or pathogen within a harvested watershed or culture facility.

Our assessment of the Ontario fishery identifies certain successes, and many challenges, for the current and future management of baitfish pathways. We provide only a sample of risk reduction measures that should be adopted to ensure the future integrity of these social–ecological systems. Given that most bait industries have economic and ecological values similar to other capture fisheries, we encourage managers to approach bait issues with the same tools used for commercial and recreational fisheries, such as species, effort, gear, and spatiotemporal regulations, to ensure continued productivity of bait fisheries in North America.

ACKNOWLEDGMENTS

We thank H. H. Harvey for many discussions about bait fisheries that improved the scope and clarity of our assessment. Two reviewers provided insightful comments that greatly improved this article. D. Marson and A. Price assisted with empirical sampling. L. Bouvier and J. Drake digitized images used in Figures 4 and 5.

FUNDING

Funding to D. A. R. Drake was provided by a Natural Sciences and Engineering Research Council (NSERC) Post-graduate Scholarship and Visiting Fellowship, an Ontario Graduate Scholarship (OGS), and a University of Toronto Fellowship. Funding to N. E. Mandrak was provided by an NSERC Canadian Aquatic Invasive Species Network Grant and the Fisheries and Oceans Canada Aquatic Invasive Species programme. Additional in-kind or financial support was provided by the Ontario Ministry of Natural Resources, the Ontario Federation of Anglers and Hunters, and the Great Lakes Fishery Trust.

REFERENCES

Cox, E. T. 1978. Counts and measurements of Ontario lakes. Ontario Ministry of Natural Resources, Toronto, Ontario, Canada.

DFO (Department of Fisheries and Oceans Canada). 2012. Survey of recreational fishing in Canada, 2010. Fisheries and Oceans Canada, Ottawa, Ontario.

DiStefano, R. J., M. E. Litvan, and P. T. Horner. 2009. The bait industry as a potential vector for alien crayfish introductions: problem recognition by fisheries agencies and a Missouri evaluation. Fisheries 34:586–597.

Drake, D. A. R., and N. E. Mandrak. 2010. Least-cost transportation networks predict spatial interaction of invasion vectors. Ecological Applications 20:2286–2299.

———. 2014a. Bycatch, bait, anglers, and roads: quantifying vector activity and species introduction risk across lake ecosystems. Ecological Applications 24:877–894.

———. 2014b. Harvest models and stock co-occurrence: probabilistic methods for estimating bycatch. Fish and Fisheries 15:23–42. doi/10.1111/faf.12005/abstract

———. 2014c. How will invasive species impact the future of fisheries? *In* W. W. Taylor, A. J. Lynch, and N. Leonard, editors. Future of Fisheries: Perspectives for Emerging Professionals. American Fisheries Society, Bethesda, Maryland.

Dunford, L. A. 2012. 2012 Survey of North American recreational baitfish regulations. Fisheries Policy Section, Biodiversity Branch, Ontario Ministry of Natural Resources, Peterborough, Ontario, Canada.

Frazier, M., A. W. Miller, and G. M. Ruiz. 2013. Linking science and policy to prevent the spread of invasive species from the ballast water discharge of ships. Ecological Applications 23:287–289.

Goodwin, A. E., J. E. Peterson, T. R. Meyers, and D. J. Money. 2004. Transmission of exotic fish viruses. Fisheries 29(5):19–23.

Gunderson, J. L., and R. E. Kinnunen, editors. 2001. Aquatic invasive species—hazard analysis and critical control point training curriculum, 2nd edition. University of Minnesota, Duluth.

Hunt, L. M., R. Arlinghaus, N. Lester, and R. Kushneriuk. 2011. The effects of regional angling effort, angler behaviour, and harvesting efficiency on landscape patterns of overfishing. Ecological Applications 21:2555–2575.

Hunt, L. M., and N. P. Lester. 2011. The effect of forestry roads on access to remote fishing lakes in northern Ontario, Canada. North American Journal of Fisheries Management 29:586–597.

Jackson, D. A., S. C. Walker, and M. S. Poos. 2010. Cluster analysis of fish community data: "new" tools for determining meaningful groupings of sites and species assemblages. Pages 503–527 *in* K. Gido and D. A. Jackson, editors. Community ecology of stream fishes: concepts, approaches, and techniques. American Fisheries Society, Bethesda, Maryland.

Keller, R. P., A. N. Cox, C. Van Loon, D. M. Lodge, L.-M. Herborg, and J. Rothlisberger. 2007. From bait shops to the forest floor: earthworm use and disposal by anglers. American Midland Naturalist 158:321–328.

Kerr, S. J., C. S. Brousseau, and M. Muschett. 2005. Invasive aquatic species in Ontario: a review and analysis of potential pathways for introduction. Fisheries 30(7):21–20.

Kilian, J. V., R. J. Klauda, S. Widman, M. Kashiwagi, R. Bourquin, S. Weglein, and J. Schuster. 2012. An assessment of a bait industry and angler behavior as a vector of invasive species. Biological Invasions 14:1469–1481.

Litvak, M. K., and N. E. Mandrak. 1993. Ecology of freshwater baitfish use in Canada and the United States. Fisheries 18(12):6–13.

Lodge, D. M., R. A. Stein, K. M. Brown, A. P. Covich, C. Brönmark, J. E. Garvey, and S. P. Klosiewski. 1998. Predicting impact of freshwater exotic species on native biodiversity: challenges in spatial scaling. Australian Journal of Ecology 23:53–67.

Lodge, D. M., C. A. Taylor, D. M. Holdich, and J. Skurdal. 2000. Reducing impacts of aquatic crayfish introductions: new policies needed. Fisheries 25(8):21–23.

Ludwig, H. R., Jr., and J. A. Leitch. 1996. Interbasin transfer of aquatic biota via anglers bait buckets. Fisheries 21(7):14–18.

Mandrak, N. E., and B. Cudmore. 2010. The fall of native fishes and the rise of non-native fishes in the Great Lakes basin. Aquatic Ecosystem Health and Management 13:255–268.

OMNR (Ontario Ministry of Natural Resources). 2012. Fishing Ontario recreational fishing regulations summary. Ontario Ministry of Natural Resources, Peterborough, Ontario, Canada.

OMNR (Ontario Ministry of Natural Resources) and BAO (Bait Association of Ontario). 2006. The commercial bait industry in Ontario: statistical report, 2005. Ontario Ministry of Natural Resources, Peterborough, Ontario, Canada.

Page, L. M., H. Espinosa-Pérez, L. T. Findley, C. R. Gilbert, R. N. Lea, N. E. Mandrak, R. L. Mayden, and J. S. Nelson. 2013. Common and scientific names of fishes from the United States, Canada, and Mexico, 7th edition. American Fisheries Society, Special Publication 34, Bethesda, Maryland.

Poos, M. S., A. J. Dextrase, A. N. Schwalb, and J. Ackerman. 2010. The secondary invasion of the round goby into high diversity Great Lakes tributaries and species at risk hotspots: potential new concerns for endangered freshwater species. Biological Invasions 12:1269–1284.

Post, J. R., L. Perrson, E. A. Parkinson, and T. van Kooten. 2008. Angler numerical response across landscapes and the collapse of freshwater fisheries. Ecological Applications 18:1038–1049.

Rothlisberger, J. D., W. L. Chadderton, J. McNulty, and D. M. Lodge. 2010. Aquatic invasive species transported via trailered boats: what is being moved, who is moving it, and what can be done. Fisheries 35:121–132.

Sala, O., F. S. Chapin III, J. J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L. F. Huenneke, R. B. Jackson, A. Kinzig, R. Leemans, D. M. Lodge, H. A. Mooney, M. Oesterheld, N. Leroy Poff, M. T. Sykes, B. H. Walker, M. Walker, and D. H. Wall. 2000. Global biodiversity scenarios for the year 2100. Science 287:1770–1774.

Strecker, A. L., P. M. Campbell, and J. D. Olden. 2011. The aquarium trade as an invasion pathway in the Pacific Northwest. Fisheries 36:74–85.

U.S. Department of Agriculture. 2005. 2002 Census of agriculture: census of aquaculture, volume 3. United States Department of Agriculture, Special Studies Part 2, AC-02-SP-2. Beltsville, Maryland.

U.S. Department of the Interior, U.S. Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2011. National survey of fishing, hunting and wildlife-associated recreation.

Vélez-Espino, L. A., M. A. Koops, and S. Balshine. 2010. Invasion dynamics of round goby (*Neogobius melanostomus*) in Hamilton Harbour, Lake Ontario. Biological Invasions 12:3861–3875.