Fisheries and Oceans Canada | Pêches et Océans Canada
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Canadian Science Advisory Secretariat (CSAS)

Research Document 2022/023

Ontario and Prairie Region

Looking for a Needle in a Haystack: Sampling Effort to Detect and Remove Asian Carps During Response Activities in the Laurentian Great Lakes Basin

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May 2022

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-43130-7 Cat. No. Fs70-5/2022-023E-PDF

Correct citation for this publication:

Smyth, E.R.B., Koops, M.A., and Drake, D.A.R. 2022. Looking for a Needle in a Haystack: Sampling Effort to Detect and Remove Asian Carps During Response Activities in the Laurentian Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/023. viii + 51 p.

Aussi disponible en français :

Smyth, E.R.B., Koops, M.A., et Drake, D.A.R. 2022. Chercher une aiguille dans une botte de foin : Effort d'échantillonnage pour détecter et retirer les carpes asiatiques lors des activités d'intervention dans le bassin laurentien des Grands Lacs. Secr. can. des avis. sci. du MPO. Doc. de rech. 2022/023. viii + 54 p.

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ABSTRACT

Early detection and response programs can prevent or delay species invasions. The potential to detect and remove species during response activities can be informed by the relationships between species abundance, sampling scheme, the probability of capture, and response effort. These relationships were investigated for Asian carps, which have been the subject of recent response efforts in the Great Lakes basin. Simulation models were used to examine the response effort required to detect and remove Asian carps in a fixed 75 ha area. The mean relative effort to detect a single fish ranged from 0.07 to 13.48 passes of the response area given: abundances from 1 to 25 fish (0.01 to 0.33 fish/ha), probabilities of capture from 0.05 to 0.70, and an assumed systematic sampling design. Response effort required for detection decreased in a nonlinear manner as fish abundance or the probability of capture increased. The mean relative effort required for local removal was 0.72 to 69.55 passes of the response area, and a similar nonlinear relationship was observed where small increases in the probability of capture above 0.05 led to substantial decreases in effort required for local removal. Completing five passes of the response area with non-detections (and an assumed low probability of capture, i.e., < 0.15) resulted in a moderate probability ($p > 0.45$) that fish remained within the response area. In addition, the probability of capture needed to be > 0.25 for low abundances (i.e., 1 fish) and > 0.55 for high abundances (i.e., 20 fish) to result in a high probability of local removal ($p > 0.80$) with five passes of the response area. Factors including fish aggregation behaviour, the size of the response area, sampling scheme (i.e., systematic, random, repeat, and informed sampling), and fish avoidance were also examined to determine their influence on effort required for detection and local removal. Improved knowledge of occupied fish habitat and resulting informed sampling had the greatest influence on effort required for detection and local removal under most probabilities of capture and fish abundances. These results provide a preliminary assessment of the potential effort required to successfully detect and remove Asian carps during response activities in the Great Lakes basin.

INTRODUCTION

Early detection and rapid response (EDRR) is one approach for preventing or slowing species invasions (Waugh 2009, Westbrooks and Eplee 2011, Reaser et al. 2020). Implementing monitoring programs to detect invasive species allows managers to quickly identify species of concern and their geographic spread, and to capture and remove individuals to prevent further expansion. The EDRR approach has been implemented for numerous non-native taxa (e.g., vegetation [Westbrooks 2004]; amphibians and reptiles [Campbell 2007]; bark and ambrosia beetles [Rabaglia et al. 2019]) and is recommended to address potential invasions of aquatic species in the Laurentian Great Lakes (Vander Zanden et al. 2010).

An early detection and response program in the Canadian waters of the Great Lakes has been implemented by the Fisheries and Oceans Canada (DFO) Asian Carp Program to prevent the establishment of Asian carp species (Grass Carp *Ctenopharyngodon idella*, Bighead Carp *Hypophthalmichthys nobilis*, Silver Carp *H. molitrix*, and Black Carp *Mylopharyngodon piceus*). These species pose moderate to high invasion risk to the lower Great Lakes and can enter the basin through several natural or human-mediated pathways (Cudmore et al. 2011, 2017). None of the Asian carps have established within the Canadian waters of the Great Lakes, but reproduction by Grass Carp has occurred within U.S. waters of the Lake Erie basin (Chapman et al. 2013, Embke et al. 2016).

DFO's early detection and response program is designed to detect and capture Asian carps to prevent establishment in Canadian waters (Marson et al. 2018). The response program includes the deployment of strike teams following the detection of Asian carps. Detections have occurred through DFO's early detection program (see Marson et al. 2018 for a description of surveillance sites), other agencies, or through commercial or citizen detections (e.g., Colm et al. 2018). The goal of strike team deployment is to capture and remove any remaining Asian carps at the point of initial detection. The magnitude of response (i.e., number of strike teams and search effort) depends on the species, ploidy (triploid vs. diploid), and life stage of the detected individual(s), which can lead to varying time lags between initial detection and response activity. Once deployed, strike teams survey the area where the original detection occurred using multiple sampling gears (primarily boat electrofishing and trammel nets). Boat electrofishing is often completed in a systematic approach within the response area with an emphasis on suitable Asian carp habitat, while trammel nets are often set concurrently in these areas. If Asian carps are detected during this initial survey, additional strike teams may be deployed. If no additional Asian carps are detected, the response effort will conclude after a period of time that is currently based on professional judgement. Since the inception of the early detection and response program in 2013, 11 responses with strike teams have been conducted, with 13 Grass Carp captured by strike teams (DFO unpublished data). The majority of responses resulted in no subsequent detections following the initial detection; however, responses near the Toronto Islands in Lake Ontario, resulted in the capture of one Grass Carp in July 2015 and two Grass Carp in September 2015. In addition, 10 Grass Carp were captured in Lake Gibson (Thorold, Ontario) in June 2016.

Understanding the efficacy of response (i.e., the probability of detecting and removing Asian carps, if present) requires an understanding of the relationships between fishing effort and the probability of capture with detection and local removal success (see Appendix A for a glossary of terms). The probability of capture refers to the probability that an individual fish will be captured during a sampling event at an occupied site. The probability of capture (p) is defined as:

$$p = \frac{C_s}{f_s B_s}$$

where C_s = site-level catch, f_s = fishing effort within a site, and B_s = fish abundance within a site. This definition of probability of capture is also consistent with some definitions of catchability (see Arreguín-Sánchez 1996).

The probability of capture is poorly understood for Asian carps but examining the available catchability estimates and factors that influence catchability can help inform the range of probabilities of capture that strike teams may encounter when conducting a response. Although catchability has received some research focus, there are only a few estimates for Asian carps within the invaded range of the Mississippi River basin, and no estimates for the Great Lakes owing to sparse captures. The few catchability estimates that exist for Asian carps and surrogate species of similar body size and life history (i.e., Common Carp *Cyprinus carpio*, Freshwater Drum *Aplodinotus grunniens*, Smallmouth Buffalo *Ictiobus bubalus*, Goldfish *Carassius auratus* and Koi *Cyprinus rubrofuscus*) indicate that catchability may range from 0.05 to 0.70 for electrofishing (Table 1). Catchability for trammel nets remains unknown and may differ from electrofishing as catchability can vary greatly across gear types (e.g., Layher and Maughan 1984, Rogers et al. 2003, Basler and Schramm 2006, Lauretta et al. 2013). Catchability can vary across species (e.g., Bayley and Austen 2002, Schoenebeck and Hansen 2005), which may help explain the large range in catchability estimates. The large range in catchability for electrofishing may be due to factors known to influence overall catchability including: fish abundance (Wilberg et al. 2010, Alós et al. 2019), fish size (Bayley and Austen 2002, Schoenebeck and Hansen 2005, Pierce et al. 2010, Benejam et al. 2012), and habitat conditions (Pierce et al. 2010, Hicks et al. 2015). Although there are a suite of factors that can influence electrofishing catchability in general (e.g., depth and conductivity; Allard et al. 2014), direct influences on the catchability of Asian carps and surrogates (i.e., Smallmouth Buffalo, Common Carp, and Prussian Carp *Carassius gibelio*) are provided in Table 2. Many of the factors that affect catchability are expected to influence probability of capture. The variability in catchability estimates for Asian carps suggests that the probability of capture is likely to be highly variable across response areas and sites.

The objectives of this analysis were to determine: 1) the sampling effort required to capture a single individual (i.e., detection) and capture all present Asian carps (i.e., local removal) across abundances likely to be encountered by strike teams; and, 2) how response area size, sampling scheme (systematic, random, informed, and repeat sampling), fish aggregation, and fish avoidance behaviour influence these estimates. The probability of local removal given the sampling effort, as well as the probability that some fish remain in the response area for the number of sampling passes with no captures, were also examined.

Table 1. Catchability estimates for Asian carps and surrogate species based on literature describing the capture of Asian carps and surrogate species with electrofishing and seining methods. Some of these estimates of catchability match the definition of probability of capture while other consider catchability at the stock level.

Method	Species	Reported Catchability/Exploitation Rates	Estimated Catchability Based on Reported Catch[1]	Reference
Seine	Grass Carp	-	0.64–0.93	Hockin et al. 1985
Seine	Common Carp	-	0.52–0.94	Bajer et al. 2011
Seine	Common Carp	0.090–0.429	-	Neess et al. 1957
Seine	Common Carp	0.008–0.427	-	Weber et al. 2016
Electrofishing	Grass Carp	-	0.07	Cumming et al. 1975
Electrofishing	Common Carp	0.15–0.54	-	Jacobs and Swink 1982
Electrofishing	Common Carp	-	0.33	Layher and Maughan 1984
Electrofishing	Common Carp	-	0.00	Smith et al. 2017
Electrofishing	Common Carp	0.001–0.268	-	Weber et al. 2016
Electrofishing	Common Carp	0.05–0.4[2]	-	Bayley and Austen 2002
Electrofishing	Common Carp	0.6842[3]	-	Layher and Maughan 1984
Electrofishing	Smallmouth Buffalo	-	1.0[4]	Layher and Maughan 1984
Electrofishing	Freshwater Drum	0.00–0.1	-	Bayley and Austen 2002
Electrofishing	Mixed species including Koi, Goldfish, and Grass Carp	0.47	-	Hicks et al. 2006

[1] Estimate based on total fish netted or fish netted in first pass (if multiple pass sampled was conducted) against total estimated population size.

[2] Catchability coefficient varies with fish size and habitat conditions

[3] 95th Confidence interval is 0.4181–0.9503.

[4] Estimate based on an abundance of two fish.

Table 2. Factors that affect catch rates or catchability of Asian carps and surrogate species based on a sample of papers describing electrofishing (EF) or netting (NET) methods.

Category	Factor	Influence of Factor	Species	Reference
Habitat	Macrophyte Cover (EF)	Increases in macrophyte cover led to lower predicted catchability estimates	Common Carp	Bayley and Austen 2002
Stock	Fish Size (EF)	An optimum in catchability was found in fish size where predicted catchability was highest in 30 cm fish but decreased with increasing or decreasing length	Common Carp	Bayley and Austen 2002
Sampling	Herding – Sound (NET)	Use of sound for herding increased CPUE	Bighead Carp	Butler et al. 2019
Sampling	Herding – Electrical (NET)	Use of electricity for herding increased CPUE	Silver Carp	Butler et al. 2019
Sampling	Herding – Electrical (NET)	Use of electricity for herding increased CPUE	Bighead Carp	Butler et al. 2019
Sampling	Herding – Electrical (NET)	Use of electricity for herding increased CPUE	Smallmouth Buffalo	Butler et al. 2019
Sampling	Net Construction [Mono- vs Multifilament nets] (NET)	Monofilament inner walls and monofilament outer walls were more effective at capturing fish	Common Carp	Balık and Çubuk 2004
Sampling	Net Construction [Mono- vs Multifilament nets] (NET)	Monofilament inner walls were more effective at capturing fish	Prussian Carp	Balık and Çubuk 2004
Sampling	Mesh Size (NET)	Catch rates were higher within 6.4 cm mesh	Silver Carp	Butler et al. 2019
Sampling	Mesh Size (NET)	Catch rates were higher within 6.4 cm mesh	Bighead Carp	Butler et al. 2019
Sampling	Mesh Size (NET)	Catch rates were higher within 6.4 cm mesh	Smallmouth Buffalo	Butler et al. 2019
Sampling	Mesh Size (NET)	Captured fish size was influenced by mesh size and should not be less 100 mm	Common Carp	Balık and Çubuk 2004
Sampling	Mesh Size (NET)	Captured fish size was influenced by mesh size and should not be less 100 mm	Prussian Carp	Balık and Çubuk 2004
Sampling	Mesh Colour (NET)	Significantly lower catch rates were found in red, green, violet mesh colours compared to white mesh. Carp catches were substantially higher in yellow nets compared to dark green.	Common Carp	Jester 1973, Balık and Çubuk 2001
Sampling	AC vs DC (EF)	Catch rates were higher in AC than DC	Black Carp	Basler and Schramm 2006
Sampling	AC vs DC (EF)	Catch rates were statistically higher in DC than AC	Common Carp	McClelland et al. 2013
Sampling	Constant vs Pulsed Current (EF)	Pulsed current resulted in significantly higher CPUE than constant current	Silver Carp	Bouska et al. 2017

METHODS

Simulation models were used to estimate the effort required to detect and locally remove Asian carps within the response area across different fish abundances and probabilities of capture, along with the effects of different sampling schemes, response area sizes, and estimates of fish aggregation or avoidance. Effort was characterized as either the number of sampled sites (absolute effort), or the number of complete passes of the response area (relative effort) in which all sites are sampled, until detection or local removal. The simulation models were designed to represent sampling methods that can actively search throughout the response area, and thus are reflective of boat electrofishing methods. However, the models can be applied to other gears (e.g., trammel netting, or electrofishing combined with trammel netting) if the gear can be fished in an active matter. In addition, time spent sampling at each site (used to bound the potential sampling time required) and range of probability of capture estimates may vary across different gear types. The simulation models encompass any of the four Asian carp species, as interspecific differences in the probability of capture and fish behaviour (e.g., assignment in the response area) were not incorporated. All analyses were completed in R v.3.6.3 in the RStudio interface (RStudio Team 2018).

BASE MODEL

The base model used a ~ 75 ha response area, which represented the typical size of a response areas visited by DFO strike teams (D. Marson, DFO, pers. comm.). Previous response areas include: the Grand River (~ 10 ha response area); Toronto Islands (~ 90 ha); Jordan Harbour (~ 130 ha); and, Lake Gibson (~ 140 ha; DFO unpublished data). For simplicity, the response area was divided into a 173 x 173 square matrix with each of the 29,929 grid cells (hereby referred to as a site) as 0.0025 ha (25 m^2). The spatial resolution of the response area matrix was designed to manage computational complexity of the model as well as reflect the area effectively sampled by a boat electrofisher during a few seconds of shocking; however, netting could also be interpreted in a similar fashion, depending on deployment methods. Assuming that sampling a site required 10 seconds, strike teams would require ~ 83 hours of systematic sampling to complete a single pass of the ~ 75 ha response area.

Different fish abundances within the response area were used to determine how effort for detection and local removal may be influenced by the number of fish occupying the response area. In total, eight different fish abundances within the response area were examined: 1, 3, 5, 7, 10, 15, 20, and 25 fish (corresponding densities of 0.01 fish/ha to 0.33 fish/ha). These abundances were selected as Asian carps have yet to establish within Canadian waters and, therefore, a relatively small number of individuals is likely to occur in response areas in the near term, whether due to accidental or intentional releases into the Great Lakes or as migrants from areas of western Lake Erie where Grass Carp reproduction has occurred. This range of abundances is also well within the number of captures from previous Asian carp responses within the Great Lakes, where, if assuming complete local removal, strike teams did not encounter abundances greater than 25 fish within a location.

Following the selection of an abundance value, fish were assigned to sites randomly throughout the response area matrix. Once fish were assigned to a site, they remained within the site until their subsequent capture. There is uncertainty about whether Asian carps behave in a solitary manner or whether they co-occur in small habitat patches, and if this aggregation behaviour would influence the effort required for detection and local removal. Potential aggregation behaviour was incorporated into the model by considering multiple aggregation rates (0.0, 0.25, 0.5, 0.75, and 1.0) when assigning fish to their site. Aggregation rates reflect the probability that an individual fish would be assigned to a site inhabited by other fish. As the aggregation rate increased, the total number of occupied sites decreased and the number of fish per site increased (Figure 1), with a value of 0.0 representing no co-occurrence and 1.0 representing a scenario where all fish occupy a single site. The range of aggregation rates was selected as lab-based shoaling behaviour has been observed in Asian carps (Ghosal et al. 2016) and aggregations of Common Carp have been recorded in lake systems (Bajer et al. 2011); however, aggregations may be seasonally dependent as larger aggregations occurred during winter and spawning (Penne and Pierce 2008, Bajer et al. 2011). Aggregations of Asian carps may occur within response areas as multiple Grass Carp have been caught in the same net set (e.g., Lake Gibson, where four and then three Grass Carp were captured in a single trammel net set; DFO unpublished data) and the same site (e.g., Lake Gibson, where three trammel net sets at a site resulted in the capture of eight Grass Carp; DFO unpublished data).

Sampling by strike teams within the response area was completed using a systematic sampling approach, which involved the strike team moving (sampling) through the response area matrix systematically, row by row. The simulation progressed with the strike team visiting each site. When the strike team sampled an occupied site, the capture of an individual Asian carp was based on the predetermined probability of capture. Multiple probability of capture values were considered among trials (i.e., 0.05 to 1.00 with 0.05 increments), with individual probability of capture rates remaining fixed during a trial. Therefore, if multiple fish occupied a sampling site, strike teams could catch multiple fish in a single sampling event; however, the probability of individual capture remains unaffected by the presence of additional fish. Probability of capture estimates from low (i.e., 0.05) to high (i.e., 0.70) were reported as the plausible range of catchability estimates for Asian carps and surrogate species.

The simulation models were run for 5,000 iterations for each combination of abundance, aggregation, and probability of capture values (hereby referred to as a scenario). Fish were reassigned within the response area for each iteration of each scenario based on the selected abundance and aggregation values. For each iteration, the strike team would systematically sample each site within the response area, starting at the bottom left cell of the response area matrix, until all 29,929 sites were sampled. Once strike teams encountered an occupied site, the probability that each individual fish was captured was based on the probability of capture for the scenario. If a fish was captured, the number of sites sampled until capture was recorded. The process was repeated (i.e., additional systematic passes) until all fish were captured and removed from the response area (local removal). The process was completed for subsequent iterations of a scenario and across all scenarios until all combinations of abundance, aggregation, and the probability of capture were completed. Mean absolute effort (number of sites sampled) and mean relative effort (number of complete response area passes undertaken) until the capture of the first fish (i.e., detection) and last fish (i.e., local removal) were calculated for each scenario. The probability of local removal was estimated for each scenario based on the percentile distribution of the effort required for local removal across the 5,000 iterations. A target probability of local removal of 0.80 was selected as a benchmark value to compare results, which reflects the effort required to have 80% confidence that local removal has occurred.

The probability of a given abundance of fish remaining in the response area was also calculated for each scenario and was based on the percentile distribution of the effort required for detection across the 5,000 iterations.

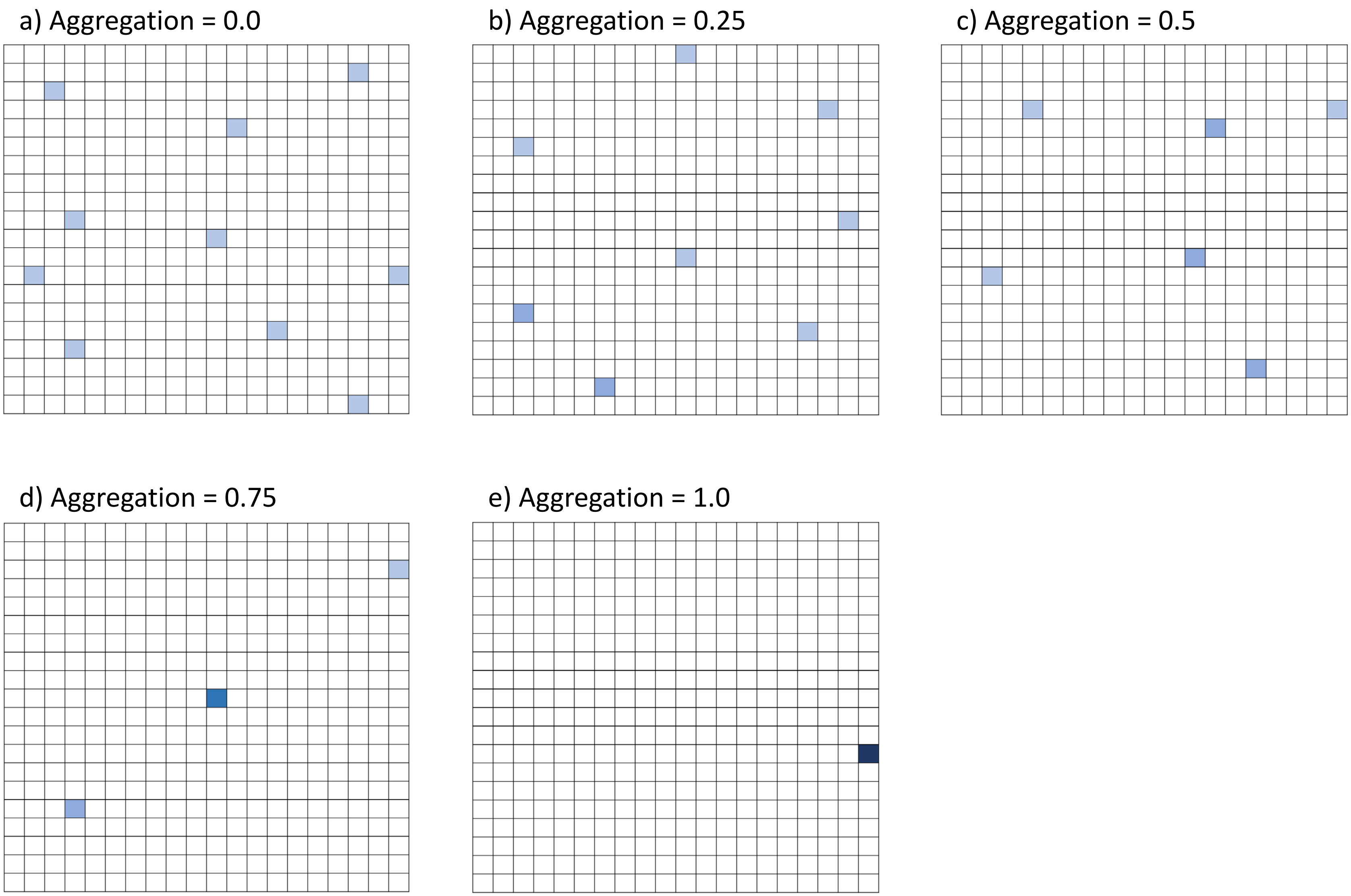

Figure 1. Hypothetical examples of ten fish distributed throughout a response area matrix with different aggregation rates. Matrix cell colour shading represents fish abundance within each cell where light colours represent low abundance (1–2 fish/cell), moderately shaded colours represent moderate abundance (5–6 fish/cell), and dark colours represent high abundance (9–10 fish/cell).

ALTERNATIVE SCENARIOS

In addition to the base model, alternative response area sizes, sampling schemes (systematic, random, repeat, and informed sampling), and fish avoidance rates were evaluated to determine their influence on the effort required for detection and local removal. These scenarios were conducted using the same range of plausible probability of capture values (p = 0.05 to 1.00; p = 0.05 to 0.70 reported) and abundance estimates (1 - 25 fish) that were used in the base model. Further details on each of the alternative scenarios is provided below. A summary table of the parameter differences between each alternative scenario and the base model is provided in Table 3.

Table 3. Summary of model parameters and corresponding values used for each model. Parameters that differ from the base model are highlighted in grey.

Parameter	***Base Model (Systematic Sampling)***	***Random Sampling Model***	***Sampling Area Size Model***	***Informed Sampling Model***	***Repeat Sampling Model***	***Fish Avoidance Model***
Response Area	75 ha	75 ha	75 ha, 37.5 ha, 18.75 ha	75 ha	75 ha	75 ha
Sampling Area	75 ha	75 ha	75 ha, 37.5 ha, 18.75 ha	75 ha (large buffer), 37.5 ha (small buffer), 18.75 ha (small buffer)	75 ha	75 ha
Probability of Capture	0.05–1.00	0.05–1.00	0.05–1.00	0.05–1.00	0.05–1.00	0.05–1.00
Fish Aggregation Rates	0.00, 0.25, 0.50, 0.75, 1.00	0.00, 0.25, 0.50, 0.75, 1.00	0.00, 0.25, 0.50, 0.75, 1.00	0.00, 0.25, 0.50, 0.75, 1.00	0.00, 0.25, 0.50, 0.75, 1.00	0.00, 0.25, 0.50, 0.75, 1.00
Sampling Scheme	Systematic	Random	Systematic	Systematic (Informed)	Systematic (Repeat)	Systematic
Sampling Events per Site	1	1	1	1	1, 3, 4, 5	1
Fish Avoidance Probability	0	0	0	0	0	0.00, 0.05, 0.25, 0.50, and 0.75

Response Area Size

The relative effort (# of complete response area passes) and mean absolute effort (# of sites sampled) required to detect and locally remove fish were evaluated across different response area sizes. In the base model, the effort required to capture fish within an area of ~ 75 ha was evaluated; however, the response area is typically delineated in the field according to site conditions and local environmental characteristics rather than a fixed size, as indicated by past response areas ranging from ~ 10 to ~ 140 ha (DFO unpublished data). Therefore, response area sizes of ~ 37.5 ha (50% of base model response area) and ~ 18.75 ha (25% of base model response area) were used to evaluate the influence of response area size. On relative effort (# of complete response area passes) to determine if results were scale-dependent and could be effectively scaled.

Random Sampling

The effect of a random sampling scheme was evaluated by calculating the mean absolute effort (# of sites sampled) required to detect and locally remove Asian carps based on randomly sampling sites (with replacement) within a response area. Unlike the systematic sampling employed in the base model, in the random sampling scenario, some sites may be sampled several times and others may remain unsampled before all carp are captured. Random sampling without replacement (i.e., all sites must be sampled before any sites can be resampled) was not evaluated as it was relatively similar to the systematic sampling approach (in both approaches, all sites would be visited once before resampling occurred). Random sampling with replacement was expected to provide a more distinct comparison to the base model and similar approaches have been utilized in the field (e.g., Lake Gibson) with some sites resampled before the entire response area was completed.

Informed Sampling

In the base model, fish were allocated randomly throughout the response area and strike teams sampled the entire response area. However, Asian carps may preferentially occupy sites having certain habitat attributes and sampling effort beyond these sites may lead to wasted effort. For example, previous response areas (e.g., Lake Gibson and the Toronto Islands) have deep water habitat that may not be used by Asian carps given their preference for depths of 1 m to < 5 m (MacNamara et al. 2018, Prechtel et al. 2018). The importance of other habitat attributes has been identified, such as Grass Carp preferring shallow, vegetated habitat (see Cudmore and Mandrak 2004) as well as complex structure like large woody debris (Weberg et al. 2020). The influence of informed sampling was evaluated by randomly assigning Asian carps to sites within a subsection of the ~ 75 ha response area that was considered suitable (i.e., 37.5 ha or 18.75 ha). These spatial aggregations were fixed to either the right side of the response matrix (i.e., 37.5 ha) or the upper right quadrant of the response matrix (18.75 ha). The proportion of unoccupied sites within these response area subsections was smaller than the base model; however, the magnitude of this proportion varied across fish abundances and aggregation rates. The influence of strike teams being informed of the suitable habitat within the response area was evaluated by comparing the effort required for detection and local removal when strike teams sampled the entire ~ 75 ha response area (i.e., large buffer scenario) or when strike teams only sampled the subsection of the response area where fish were assigned (i.e., small buffer scenario). The large buffer scenario can reflect situations where strike teams are unaware of habitat preferences, were aware of habitat preferences but sampled the entire response area for redundancy, or were aware of habitat preferences but were unable to define suitable habitat within the response area. In the large buffer scenario, strike teams were modelled to begin sampling at the bottom left corner of the 75 ha response area to represent a worst-case scenario as strike teams would be sampling large areas of unoccupied habitat before they began sampling the suitable habitat. The sensitivity of the spatial aggregation locations within the response area were not examined in this analysis.

Repeat Sampling

The influence of immediate, repeated sampling at a site on the effort required for local removal was determined. In the base model, each site was sampled once during a complete pass of the response area; however, in practice, strike teams may immediately resample sites where Asian carps are captured, particularly when the probability of capture is suspected to be < 1.0 (e.g., Lake Gibson where three trammel net sets occurred at the same location and resulted in one, three, and four fish captured, respectively; DFO unpublished data). The repeat sampling scenario reflected the situation where strike teams will immediately resample a site following the capture of a single fish during the initial visit to the site; however, immediate resampling was not conducted if fish remained undetected following the initial sampling at a site. Multiple repeat sampling rates were considered (i.e., 3, 4, and 5 sampling events in total following initial detection) and effort required for local removal was compared against base model results. The number of total sampling events per site was fixed throughout the scenario regardless of number of fish captured at the initial sampling event or if additional fish were captured during subsequent sampling events. Repeat sampling was conducted with aggregation rates fixed at 0.75 and 1.0, as repeat sampling would likely be sensitive to this behaviour.

Fish Avoidance

Fish avoidance was incorporated into the model by examining the probability that fish would move among sites within the response area based on the presence of nearby strike teams during a response. Fish may respond to boat activity during electrofishing and/or net deployment as sound (through speakers and boat engines) has been successfully used to herd fish (Butler et al. 2019); therefore, it is possible that fish may actively avoid strike teams and evade capture. Fish avoidance was incorporated into the model by considering the probability that fish may depart a site immediately prior to sampling and be randomly assigned to a different site within the response area. Aggregated fish within the site either departed and relocated or remained within the site as a group, as it was assumed that fish aggregations would remain intact despite avoidance behaviour. A wide range of potential avoidance probabilities were considered (0.05, 0.25, 0.50, and 0.75) given the relative uncertainty in the avoidance of Asian carps during a response.

SENSITIVITY ANALYSIS

The influence of each alternative scenario and aggregation behaviour on relative response effort was determined by calculating the difference in mean number of passes (or number of sampling periods where 29,929 sites were sampled) and the percent change in mean absolute effort required for the detection and local removal of Asian carps. Four potential combinations of abundance and probability of capture values, with aggregation fixed at 0.5, were considered to illustrate distinct situations that strike teams may face:

1. low abundance and low probability of capture (3 fish and a probability of capture of 0.05);
2. low abundance and high probability of capture (3 fish and a probability of capture of 0.70);
3. high abundance and low probability of capture (25 fish and a probability of capture of 0.05); and,
4. high abundance and high probability of capture (25 fish and a probability of capture of 0.70).

The base model results of each combination were compared to results when: aggregation rate was increased to 0.75 (aggregation), sampling was random (random sampling), repeat sampling occurred with 3 samples per site (repeat), fish occupied only 50% of the base response area but sampling occurred throughout the entire 75 ha sampling area (large buffer), sampling occurred only in 50% of the base response area where fish occurred (small buffer), and fish avoidance increased to 0.25 (avoidance). These values were selected to represent moderate changes to parameter value based on the range of values considered for each scenario. In total, 24 model scenarios were computed to evaluate the sensitivity of results to parameters and sampling schemes. A more detailed analysis of the sensitivity of the results to different parameters was conducted with probability of capture rates of 0.05, 0.25, 0.50, 0.70, and 1.00, which is provided in Appendix B.

RESULTS

A summary of results is provided below. Detailed results for all model scenarios are provided in an accompanying data report (Smyth et al. 2021). The range in model results for effort and probability outcomes varied greatly between scenarios. To keep values standardized, the results are presented to two decimal points; however, this level of precision may be an overestimate given the nature of the simulation models.

BASE MODEL RESULTS

The effort required to detect the presence of Asian carps (i.e., catch at least one fish; detection) was influenced by both the probability of capture and fish abundance. Mean relative effort required for detection ranged from 0.07 to 13.48 passes of the total response area. As the probability of capture increased, the amount of effort required for detection decreased in a nonlinear manner (Figure 2). For example, when the probability of capture was 0.05, 13.48 passes were, on average, required for detection when abundance was one fish; however, when the probability of capture was increased to 0.25, only 2.42 passes, on average, were required for detection. Effort required for detection also decreased as fish abundance increased. For example, when the probability of capture was 0.05, only 4.64 passes were required, on average, when abundance was three fish compared to 13.48 passes, on average, required when abundance was one fish.

Aggregation behaviour had a small influence on the relative effort required for detection except when abundance and aggregation rates were high (Figure 3). For example, when abundance was 25 fish and the probability of capture was 0.70, mean relative effort was 0.50 passes when the aggregation rate was 1.00, 0.07 passes when the aggregation rate was 0.50, and 0.04 passes when the aggregation rate was 0.00. When the probability of capture was fixed, the relative effort required for detection decreased as the probability of fish occupying sites close to the initial sampling site increased. When aggregation rates were low (i.e., 0.00), each fish occupied a site in isolation. In this situation, the probability of at least one fish occupying a site close to the initial sampling site was greater than when aggregation rates were high (i.e., 1.00), where all fish occupied a single site within the response area.

The probability that *n* fish occupied the response area decreased with an increasing number of passes without the capture of Asian carps (i.e., empty passes) (Figure 4). The number of empty passes required to reach a low probability ($p = 0.20$) of fish present in the response area decreased with increasing probability of capture and abundance (Figure 5). For example, the probability that 15 fish or more were present was $p \sim 0.02$ at five empty passes, even at very low probabilities of capture ($p = 0.05$). These results also demonstrated that five empty passes resulted in a moderate probability ($p > 0.45$) that fish remained within the response area (i.e., abundance = 1 fish) when the probability of capture was low ($p < 0.15$) (Figure 4), indicating the extensive effort required to ensure a high confidence of detection, particularly when the probability of capture is low.

The mean relative effort required for local removal was substantially greater than the effort required for detection and ranged from 0.72 to 69.55 passes. As the probability of capture increased, the amount of effort required for local removal decreased in a nonlinear manner (Figure 6). For example, when abundance was five fish and the probability of capture was 0.05, 40.36 passes were, on average, required for local removal, but 7.16 passes, on average, were required when the probability of capture was increased to 0.25. Effort required for local removal increased as fish abundance increased. For example, when the probability of capture was 0.05, 13.48 passes, on average, were required when abundance was one fish compared to 31.25 passes, on average, when abundance was three fish. In addition, aggregation behaviour had a small effect on mean relative effort required for local removal (Figure 7).

The relationship between local removal and the number of response area passes demonstrated that even five passes were insufficient to have a high probability of local removal under many situations (Figure 8). When effort was fixed, a greater probability of capture was required at large abundances to achieve similar results as smaller abundance. For example, to achieve a high probability of local removal ($p = 0.80$) within five passes, the probability of capture needed to be $p > 0.25$ for low abundances (i.e., 1 fish) and > 0.55 for high abundances (i.e., 20 fish) (Figure 9). Given the potential probability of capture range of 0.05 to 0.70, five passes of the response area would result in local removal probability of $p = 0.22$ to $p > 0.99$ at low abundances (i.e., 1 fish) and $p < 0.01$ to $p = 0.95$ at high abundances (i.e., 20 fish).

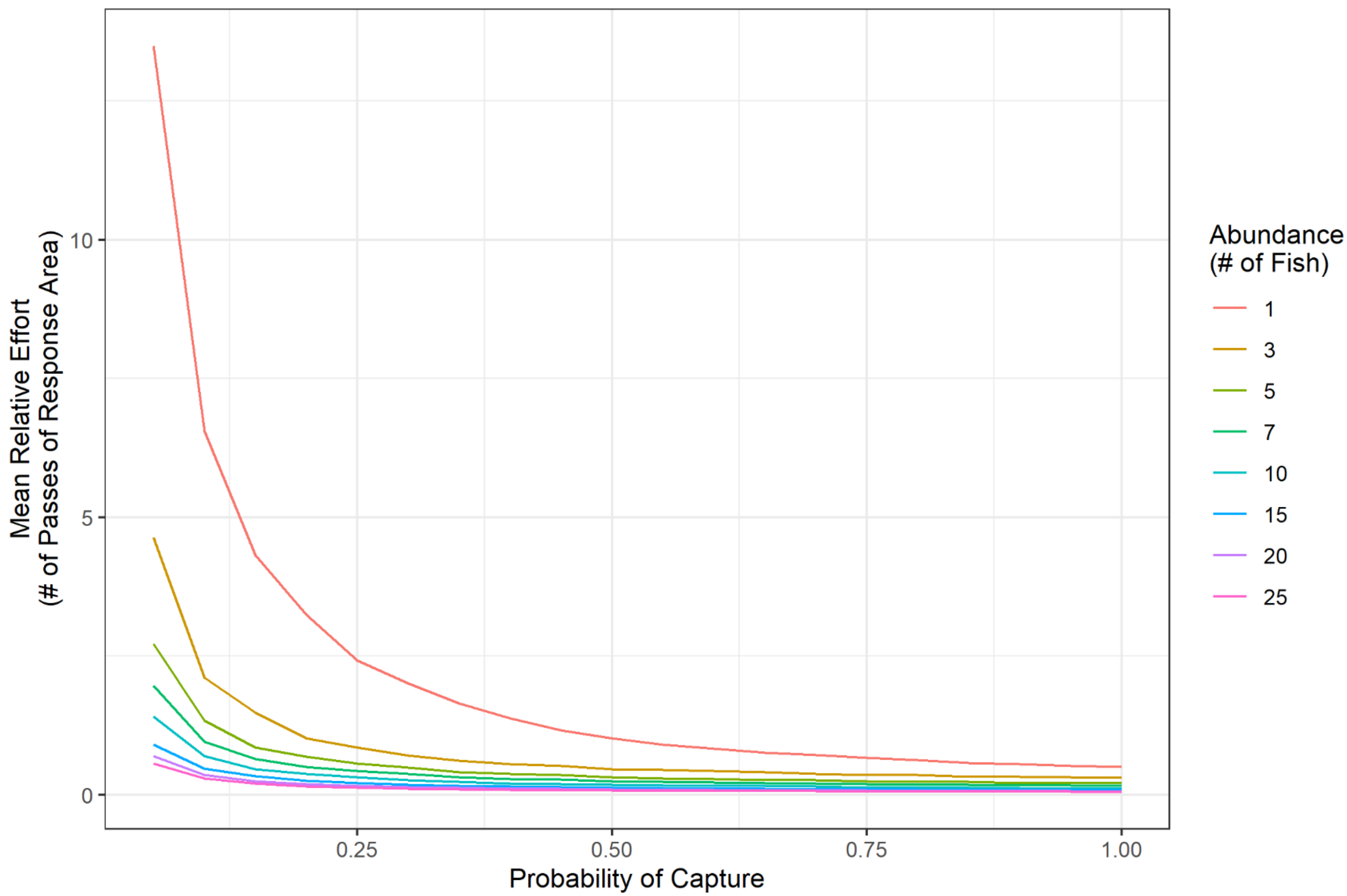

Figure 2. Mean relative effort (# of passes) required for detection of a single Asian carp individual in relation to the probability of capture and fish abundances (i.e., 1, 3, 5, 7, 10, 15, 20, and 25 fish) given systematic sampling and an aggregation rate of 0.50.

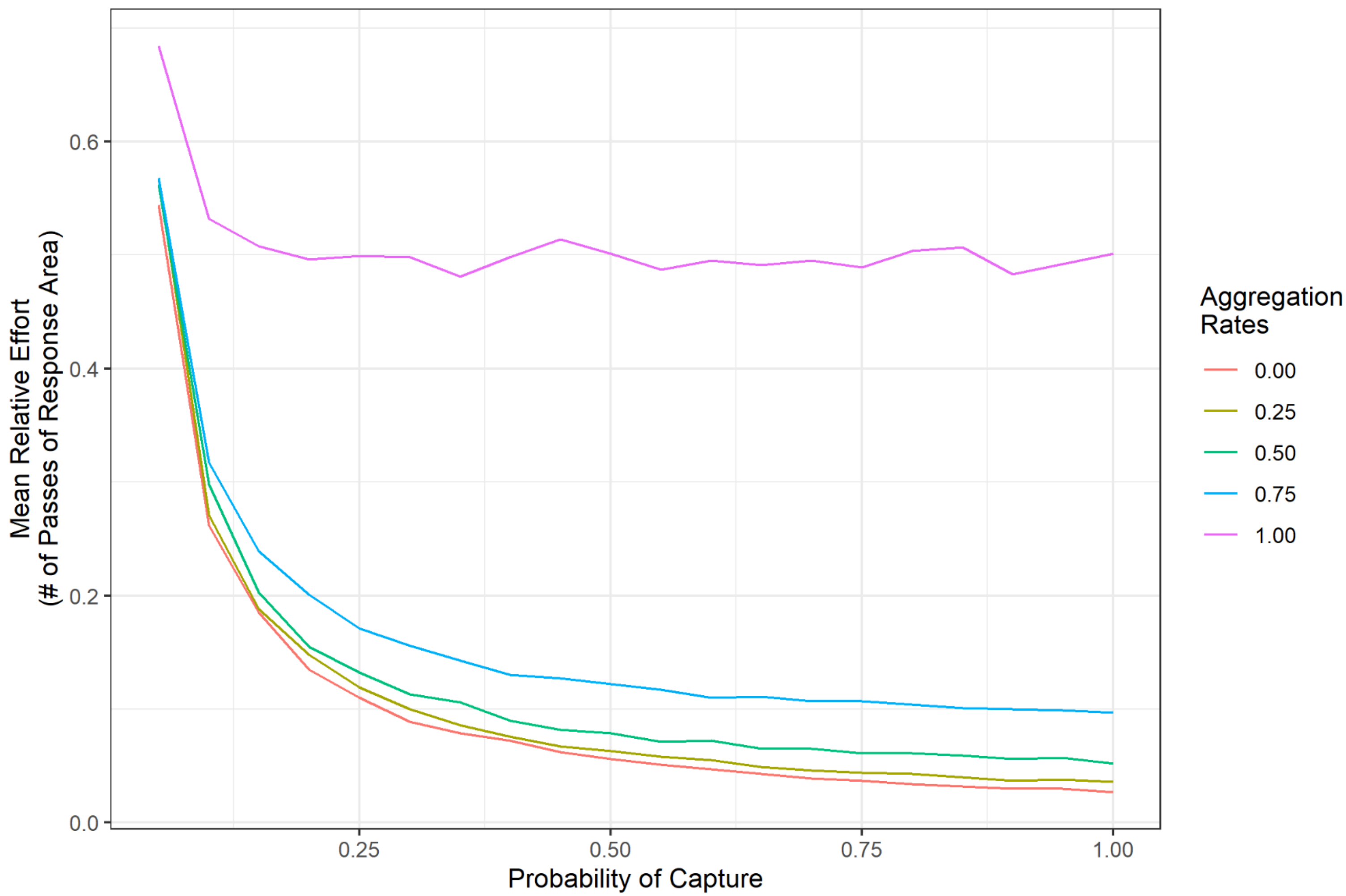

Figure 3. Mean relative effort (# of passes) required for detection of a single Asian carp individual in relation to the probability of capture and aggregation rates within the response area (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00), given systematic sampling and an abundance of 25 fish.

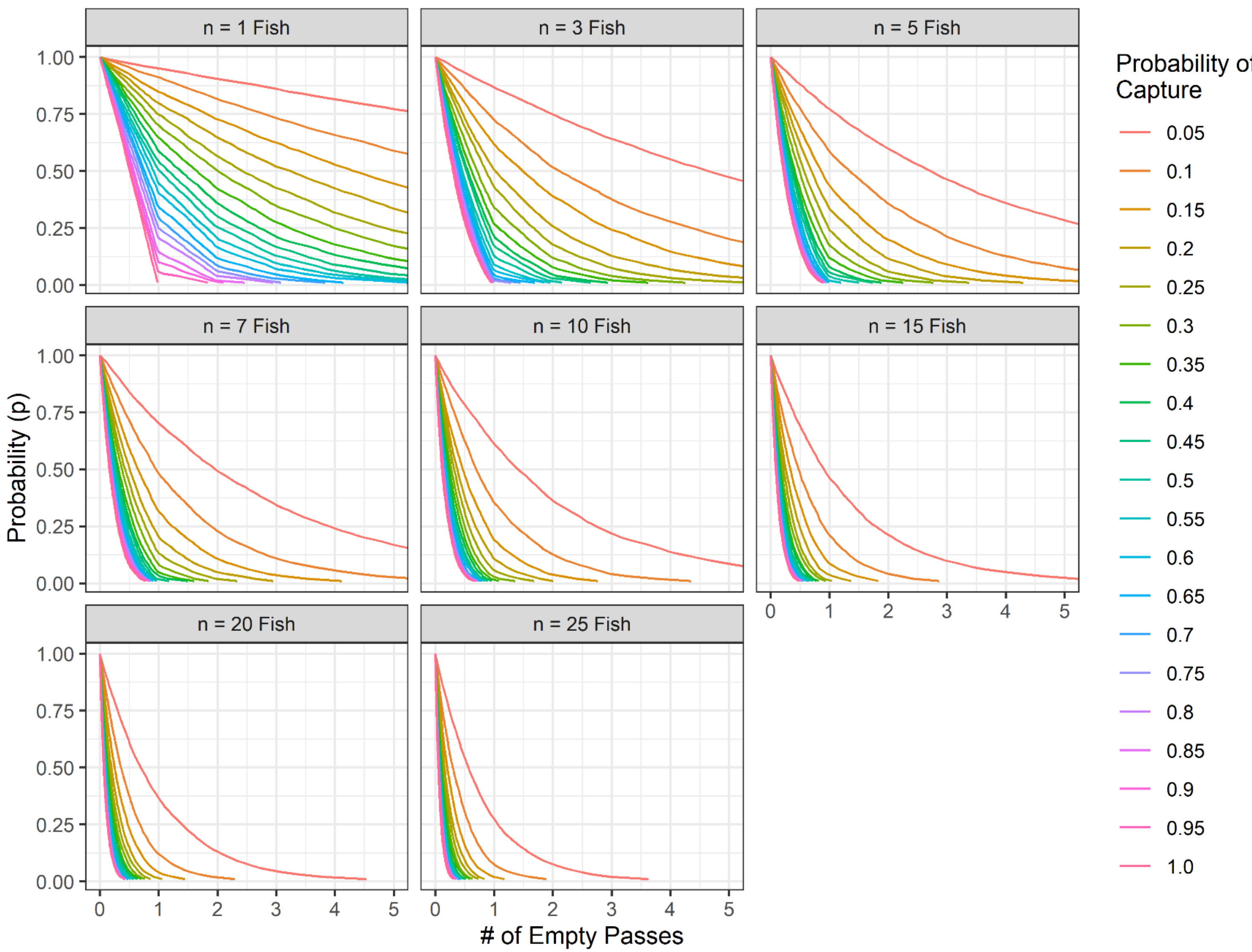

Figure 4. Probability of n Asian carps occupying the response area (see inset labels on grey bars) given the number of empty passes completed by strike teams when the aggregation rate is 0.50 across different fish abundances. The lines within the graph represent probability of capture values ranging from 0.05 to 1.00.

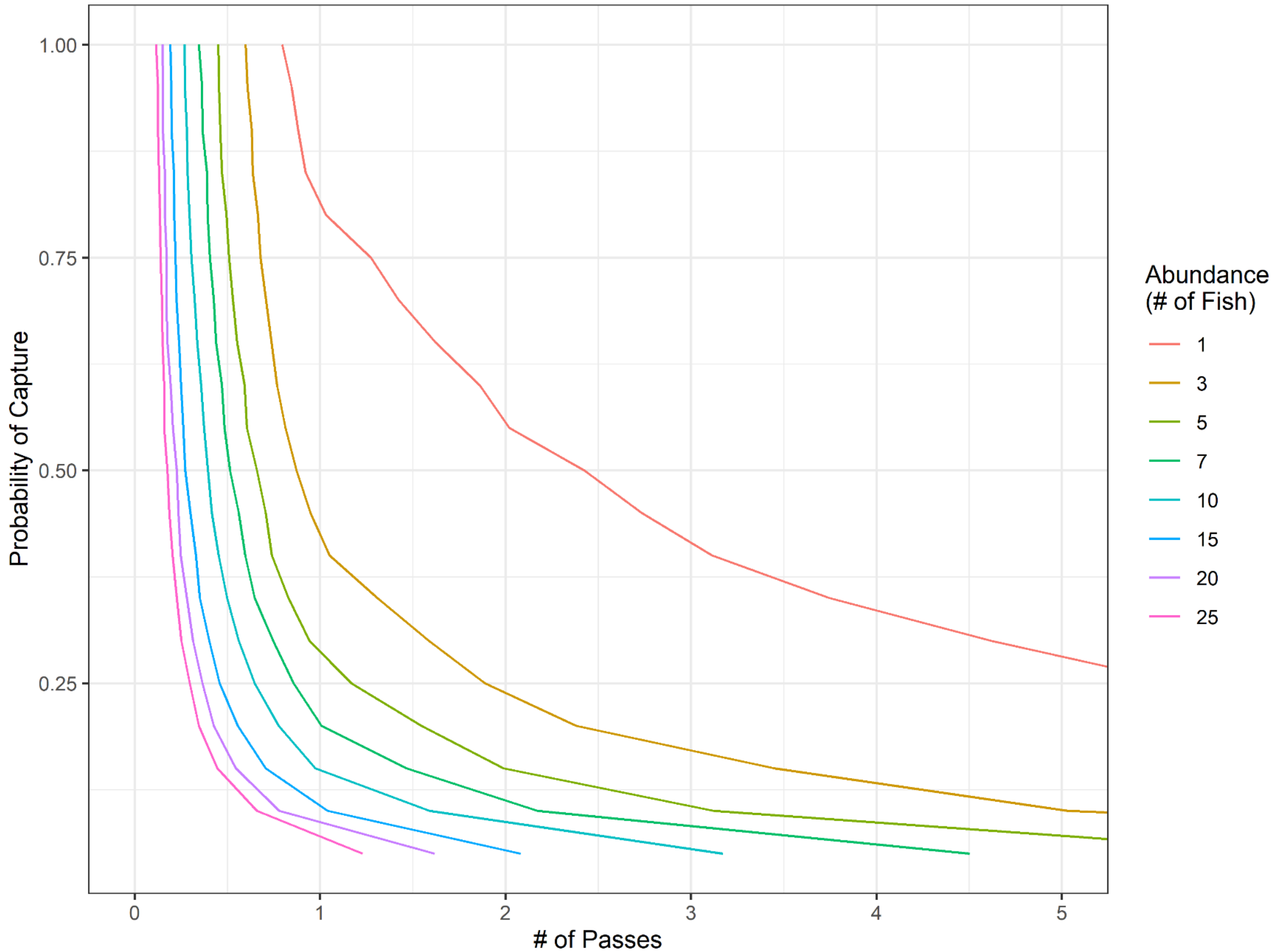

Figure 5. The minimum probability of capture required to obtain a ≤ 0.20 probability that a set abundance of Asian carps are occupying the response area given the number of empty passes completed by strike teams. Simulations are based on an aggregation rate of 0.50.

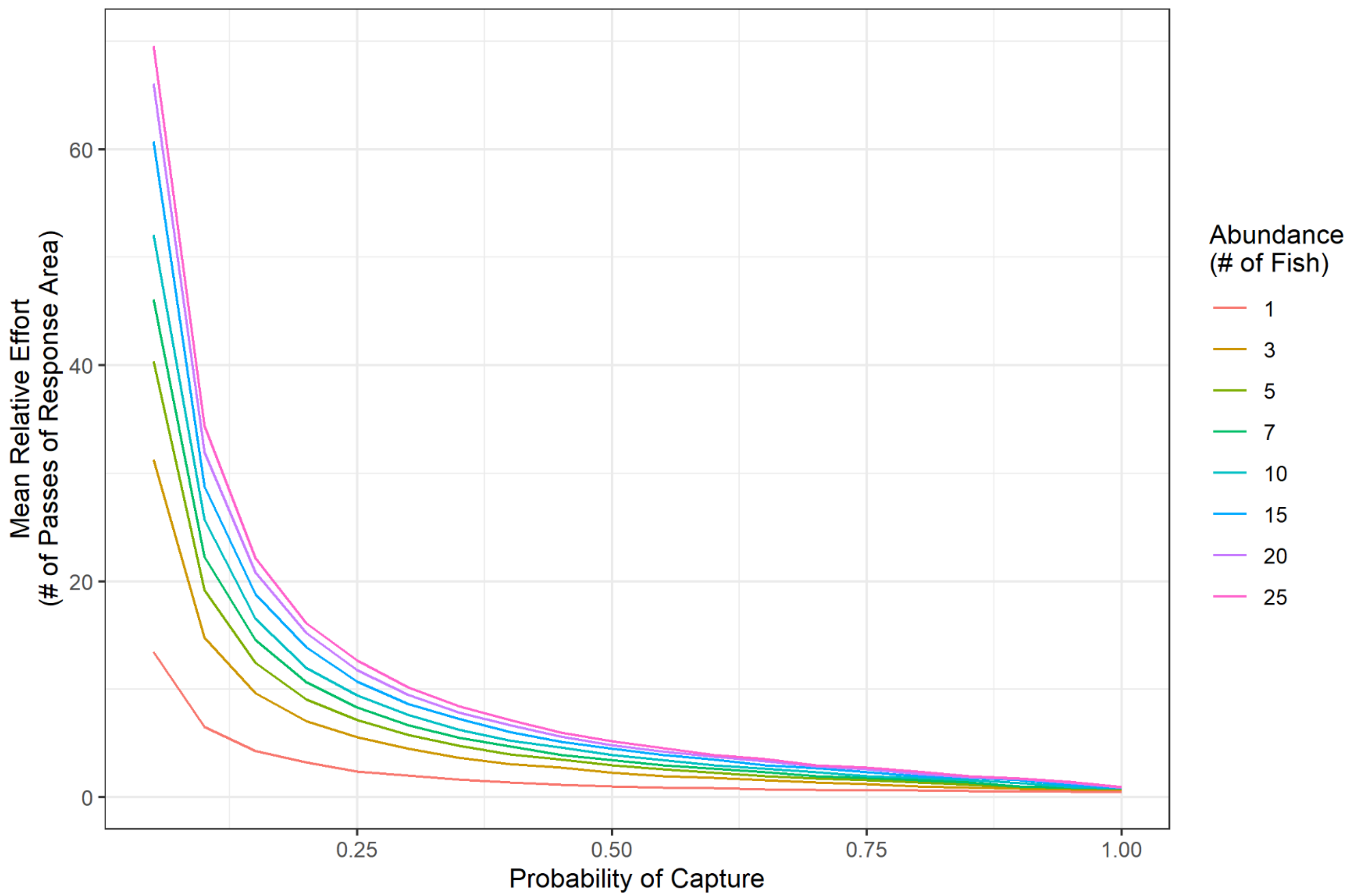

Figure 6. Mean relative effort (# of passes) required for local removal in relation to the probability of capture and fish abundance within the response area (i.e., 1, 3, 5, 7, 10, 15, 20, and 25 fish), given systematic sampling and an aggregation rate of 0.50.

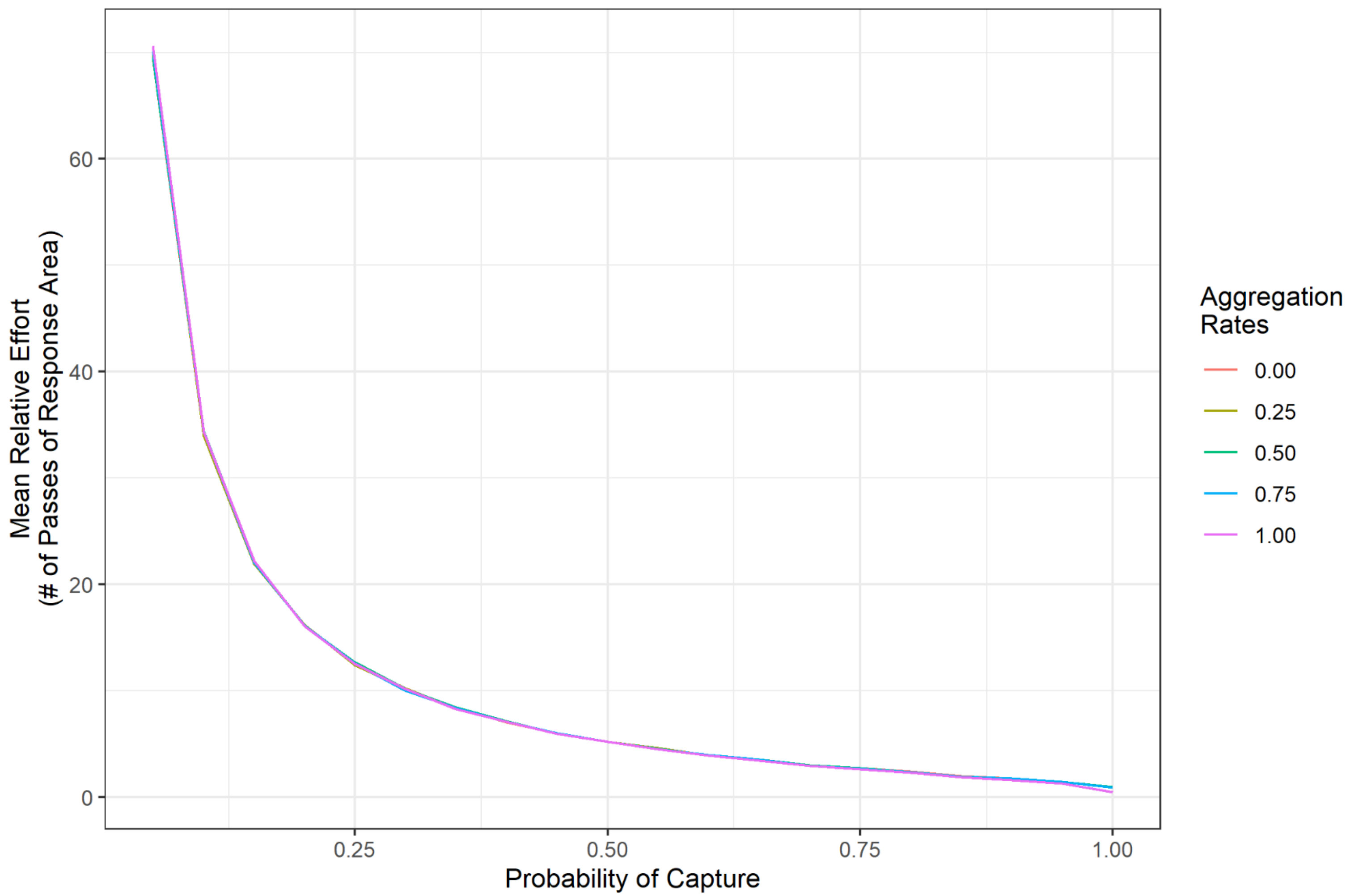

Figure 7. Mean relative effort (# of passes) required for local removal of 25 Asian carps in relation to the probability of capture and aggregation rates (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00).

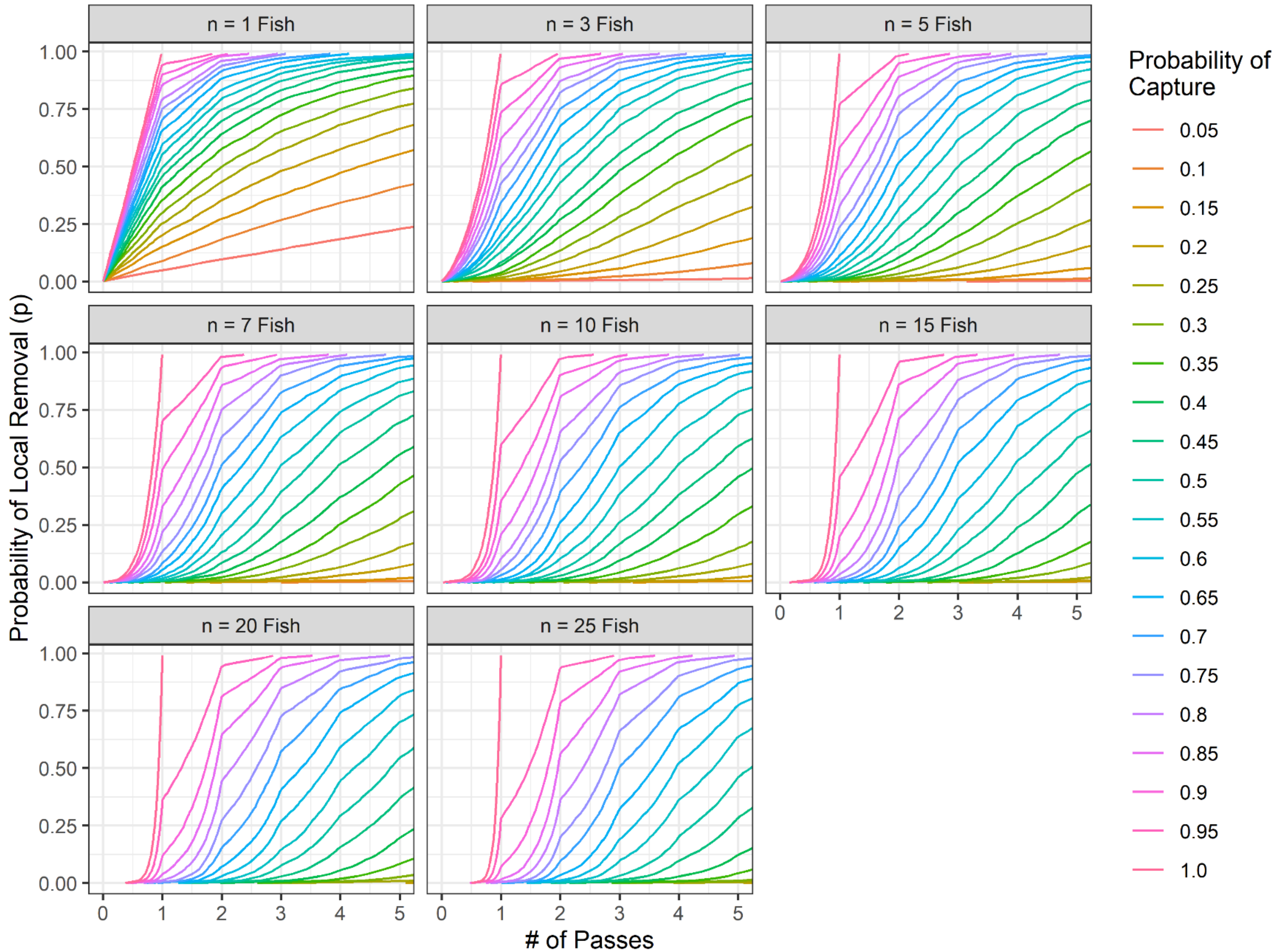

Figure 8. Probability of locally removing n Asian carps (see inset labels on grey bars) within the response area in relation to the probability of capture (0.05 to 1.00; see legend) and an aggregation rate of 0.50.

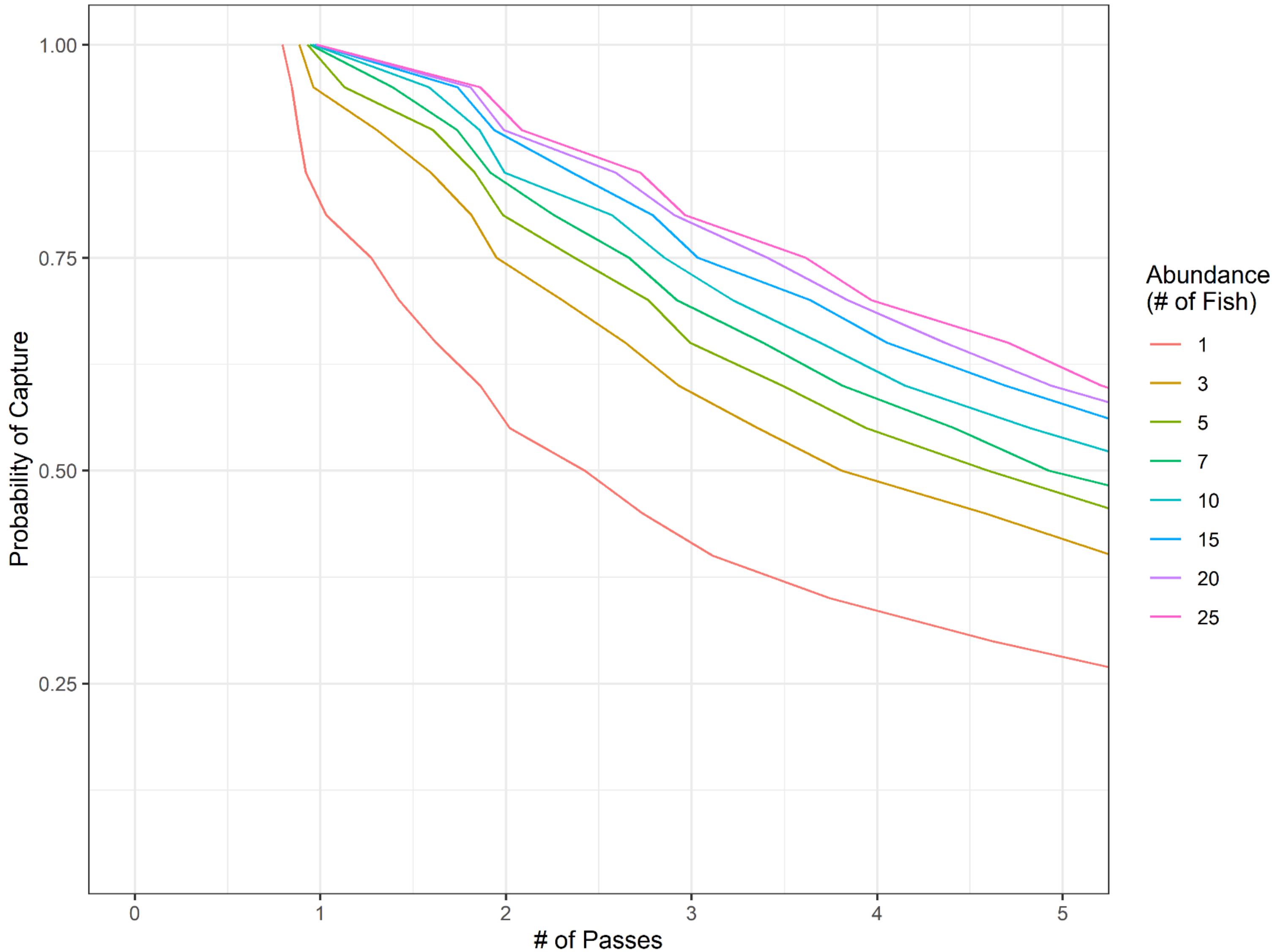

Figure 9. The minimum probability of capture required for an 0.80 probability of locally removing 1 to 25 Asian carps within the response area given the number of passes completed by strike teams. Simulations were based on an aggregation rate of 0.50.

Base Model Synthesis

The base model demonstrated that the effort required to detect the presence of Asian carps is lower when there is a higher abundance of Asian carps present, the probability of capture is high, and Asian carps exhibit a lower propensity to aggregate. The effort required to remove all Asian carps in the response area is lower when there are fewer Asian carps and when the probability of capture is high. High probability of capture values (≥ 0.65) are required to ensure high confidence of local removal in the response area after five passes.

ALTERNATIVE SCENARIOS

Response Area Size

Overall, the size of the response area had no influence on the mean relative effort (# of passes) needed for detection or local removal (Figure 10 and Figure 11; respectively), but mean absolute effort (# of sites) for detection or local removal decreased proportionally with response area. For example, when the probability of capture was 0.05, the mean relative effort required for detection for an abundance of 25 fish ranged from 0.55 to 0.59 passes across response area sizes, but absolute effort ranged from 16,809 sites (area = 75 ha), to 8,758 (area = 37.5 ha), and 4,275 sites (area = 18.75 ha). Similar results were observed for the effort required for local removal. For example, when the probability of capture was 0.05, relative effort required for the local removal of 25 fish ranged from 69.55 to 71.17 passes across response area sizes, but absolute effort ranged from 2,081,405 sites (area = 75 ha), to 1,064,955 sites (area = 37.5 ha), and 542,786 sites (area = 18.75 ha). The comparability of relative effort across response area sizes demonstrated that the model results are scalable to different response areas.

Random Sampling

The effect of random sampling (with replacement) on effort was dependent on aggregation behaviour as well as the probability of capture. Random sampling had a small influence on the effort required for detection across probabilities of capture, except at high aggregation rates, where substantially greater effort was required for detection (Figure 12). For example, when the probability of capture was 0.70 and aggregation rate was 0.25, an average of 1,430 sites were needed for detection during systematic sampling compared to 1,935 sites during random sampling. When the aggregation rate was increased to 1.00, 14,821 sites were needed for detection during systematic sampling, but 20,704 sites were needed during random sampling. The explanation for this trend is that random sampling leads to situations where unoccupied sites may be resampled multiple times until an occupied site is visited thus, additional sampling effort is required for detection.

In the case of effort required for local removal, random sampling had a small influence when probability of capture was low (0.05); however, as probability of capture increased, the influence of random sampling increased, particularly for scenarios with low to moderate aggregation rates (i.e., 0.00 to 0.75) (Figure 13). For example, when the aggregation rate was 0.00 and the probability of capture was low (0.05), the mean absolute effort required to remove 25 fish with systematic sampling was 2,079,229 sites and 2,145,335 sites when sampling was random. However, when the probability of capture was high (0.70), 89,516 sites were required for local removal with systematic sampling compared to 153,322 sites when sampling was random, representing a 71% increase. The difference observed at high probability of capture rates was due to site replacement with the random sampling approach. With random sampling, the probability of sampling an occupied site remains constant during sampling; however, during systematic sampling, the probability of sampling the occupied site increases because each site is sampled once before a pass of the response area is completed, which results in reduced sampling effort required for local removal.

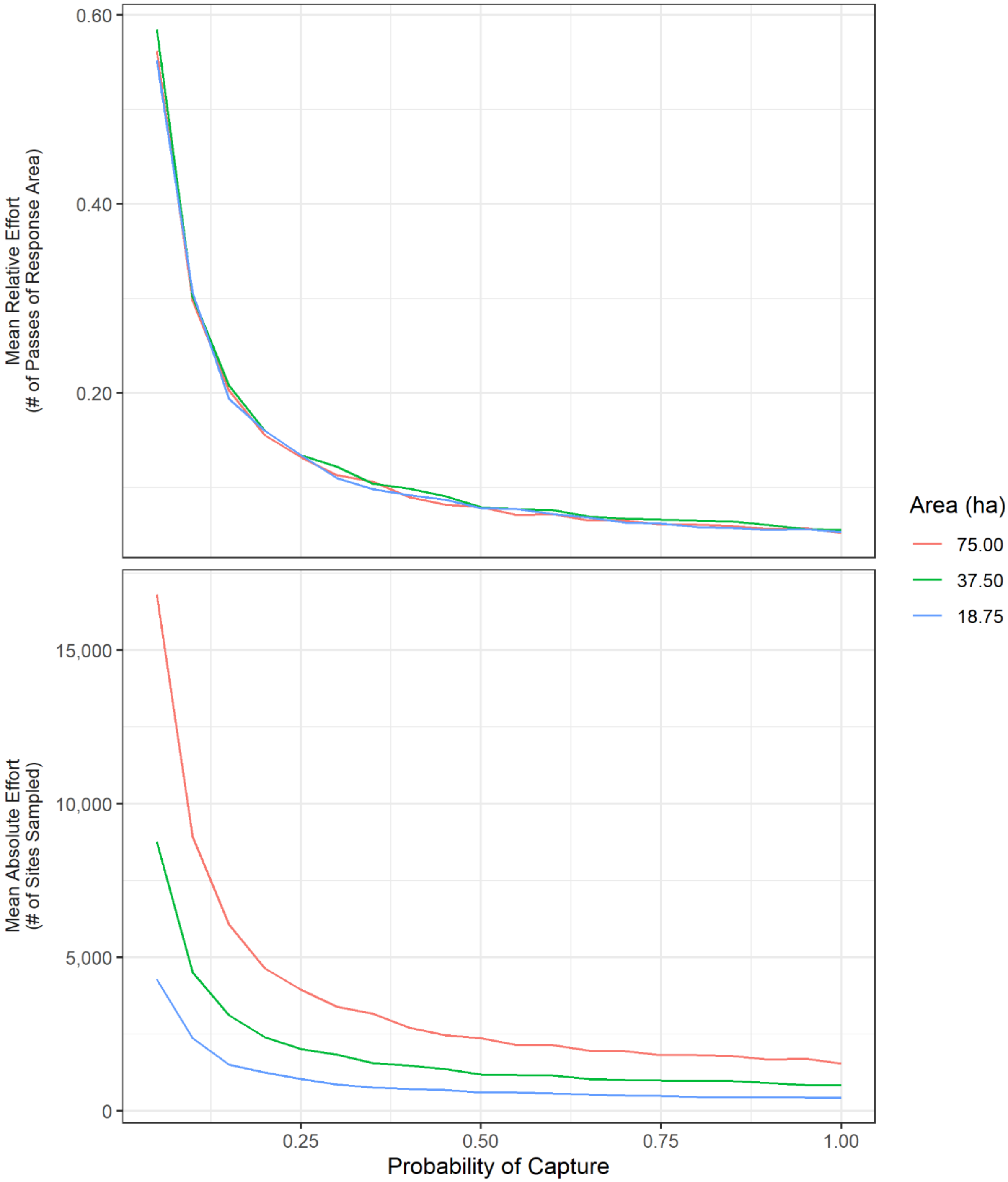

Figure 10. Mean relative effort (# of passes) (top panel) and mean absolute effort (# of sites) (bottom panel) required for detection in relation to the probability of capture and three response area sizes (75 ha, 37.5 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish and an aggregation rate of 0.50.

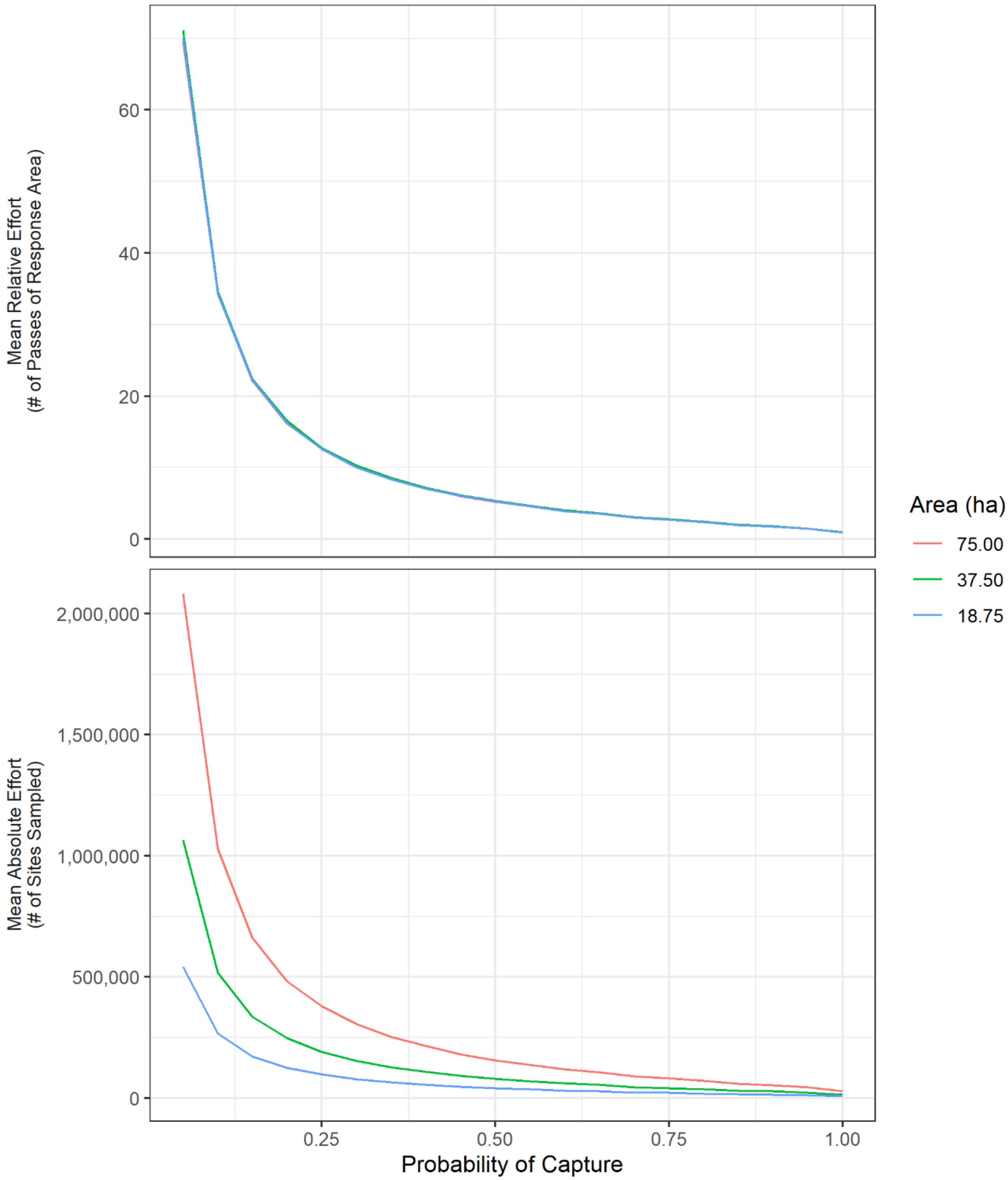

Figure 11. Mean relative effort (# of passes) (top panel) and mean absolute effort (# of sites) (bottom panel) required for local removal in relation to the probability of capture and three response area sizes (75 ha, 37.5 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish with an aggregation rate of 0.50.

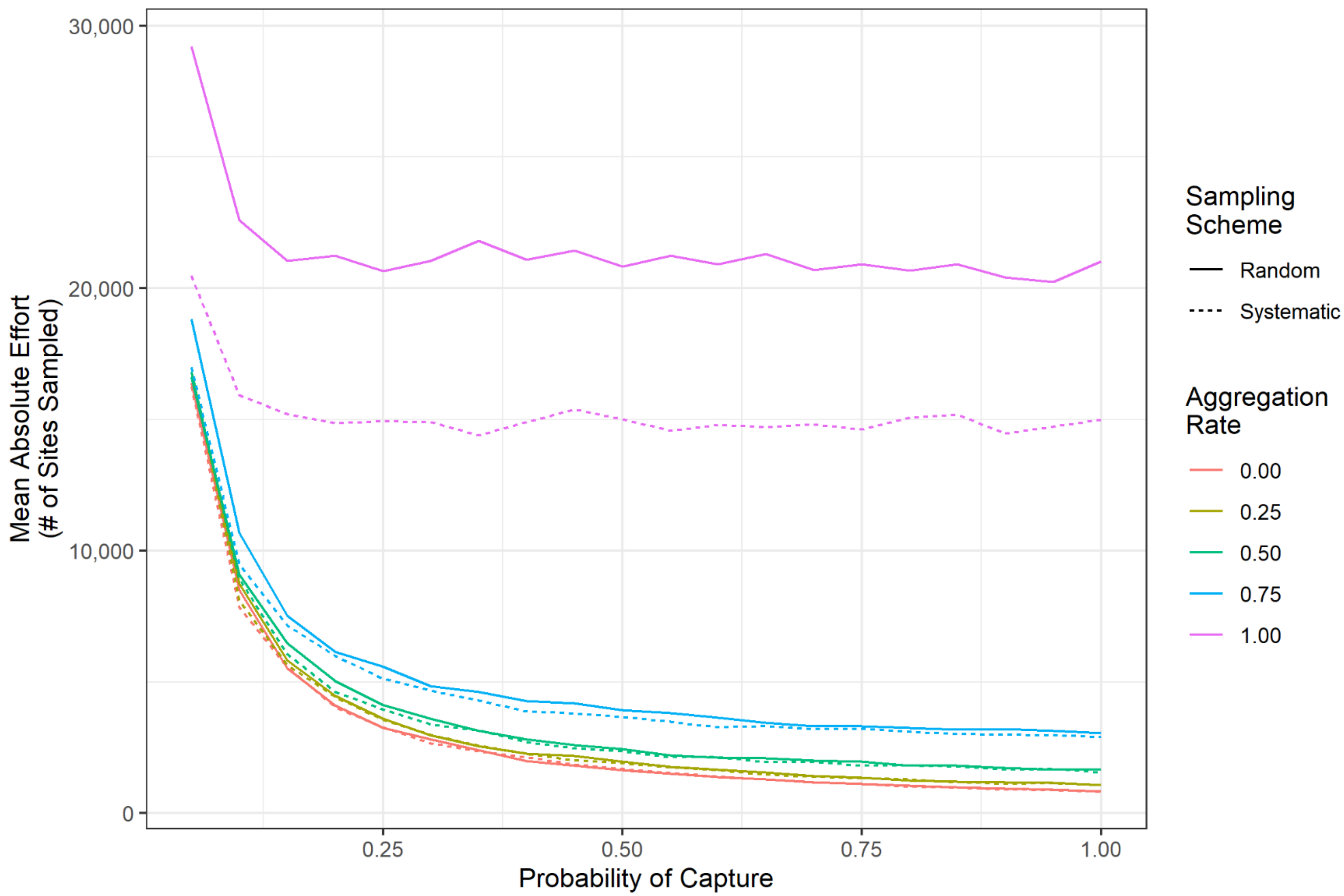

Figure 12. Mean absolute effort (# of sites) required for the detection of a single fish in a 75 ha response area in relation to the probability of capture and five aggregation rates (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00). Also shown is the effect of random and systematic sampling with an abundance of 25 fish.

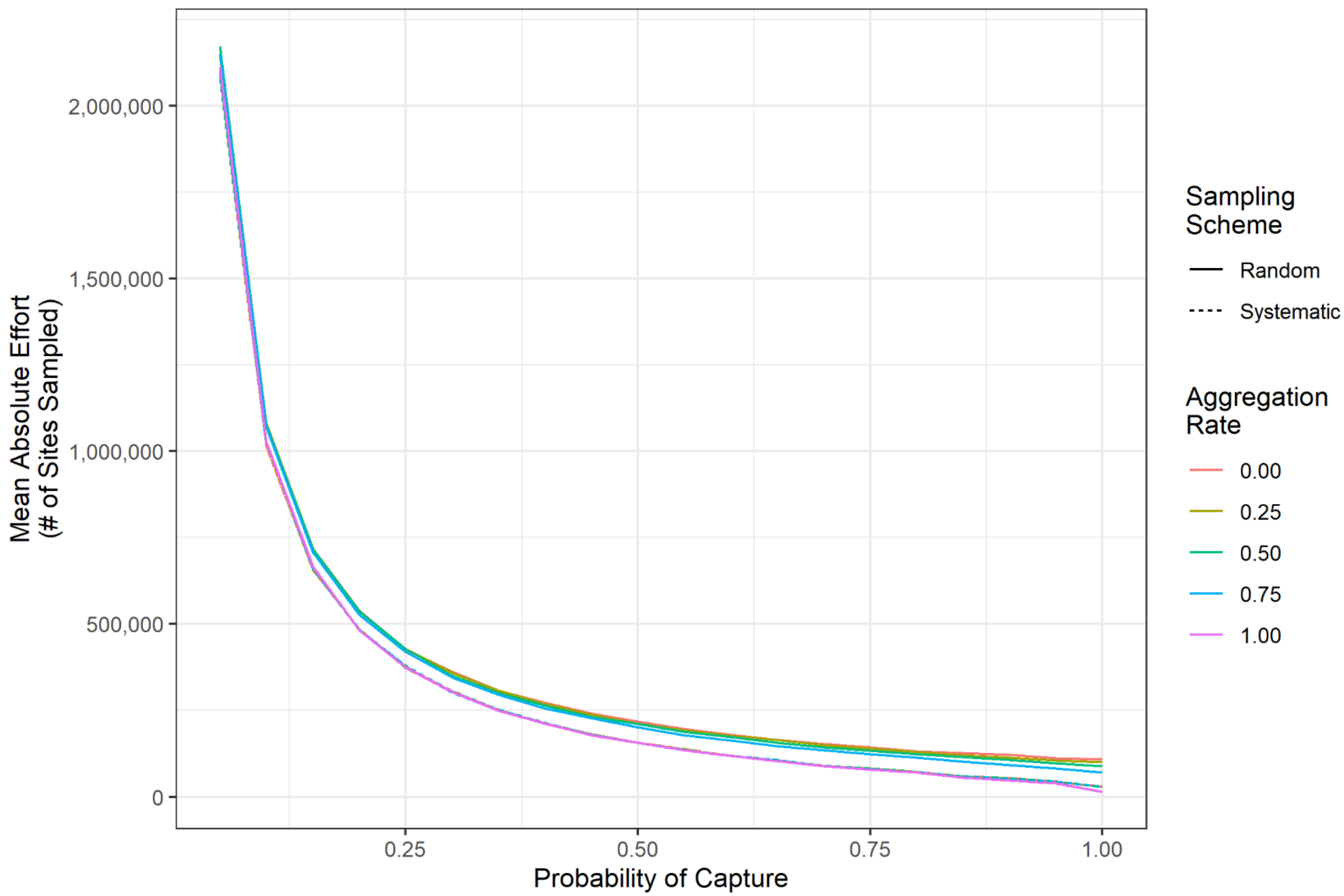

Figure 13. Mean absolute effort (# of sites) required to locally remove 25 fish in a 75 ha response area in relation to the probability of capture and five aggregation rates (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00). Also shown is the effect of random and systematic sampling with an abundance of 25 fish.

Informed Sampling

Informed sampling influenced the effort required for detection (Figure 14) and local removal (Figure 15). Informed sampling resulted in fewer mean number of sites for both detection and local removal compared to the base model results and was proportional to the amount of suitable in the response area (i.e., the effort required to capture a single fish was 50% of the base results when 50% of the response area was suitable). For example, when strike teams focused their sampling on the spatial aggregations of Asian carps (i.e., “small buffer”) and the probability of capture was low (0.05), the mean absolute effort required for detection was 16,809 sites when suitable habitat was 100% of the response area (i.e., base model; 75.00 ha), 8,758 sites when suitable habitat was 50% for the response area (i.e., 37.5 ha), and 4,275 sites when suitable habitat was 25% of the response area (i.e., 18.75 ha). These results were similar to the response area size scenario, where reducing the response area by 50% or 25% resulted in 50% or 25% less effort, respectively, for detection and local removal. Similar trends involving the implementation of the small buffer were observed for local removal. When strike teams implemented a small buffer and the probability of capture was low (0.05), mean absolute effort required for detection was 2,081,405 sites when suitable habitat was 100% of the response area (i.e., base model; 75 ha), 1,064,955 sites when suitable habitat was 50% for the response area (i.e., 37.5 ha), and 542,786 sites when suitable habitat was 25% of the response area (i.e., 18.75 ha).

More effort was required for detection and local removal when strike teams sampled the entire 75 ha response area in the presence of spatial aggregations of Asian carps (i.e., “large buffer”) compared to the small buffer scenarios. For example, when strike teams implemented a large buffer and the probability of capture was low (0.05), mean absolute effort required for detection was 18,938 sites when suitable habitat was 50% for the response area (compared to 8,758 sites when strike teams used a small buffer), and 19,977 sites when suitable habitat was 25% of the response area (compared to 4,275 sites when strike teams used a small buffer), all of which compared to 16,809 sites from the base model results. Overall, the large buffer scenario with suitable habitat covering 25% of the response area (i.e., 18.75 ha) yielded the greatest effort required compared to other scenarios across probability of capture values; however, this may have been an artefact of model design (i.e., worst-case scenario). The effort required for local removal was more comparable across scenarios. For example, when strike teams implemented a large buffer and the probability of capture was low (0.05), mean absolute effort required for local removal was 2,092,518 sites when suitable habitat was 50% for the response area (i.e., 37.50 ha), and 2,095,421 sites when suitable habitat was 25% of the response area (i.e., 18.75 ha), compared to 2,081,405 sites from the base model. The large buffer results differed substantially from the base model results for detection (Figure 14) and not local removal (Figure 15) because relatively few sites needed to be sampled for detection compared with local removal.

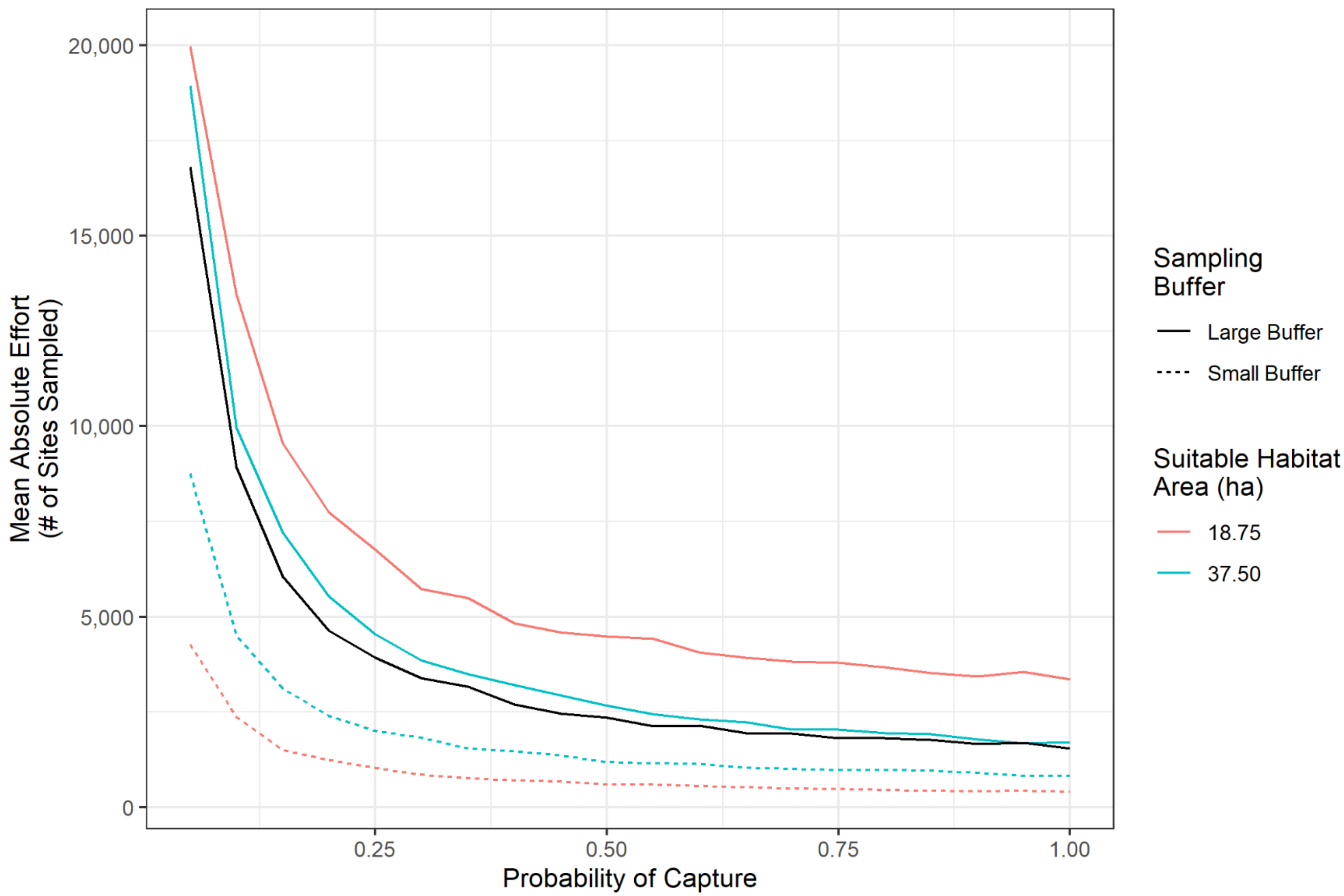

Figure 14. Mean absolute effort (# of sites) required for detection with an abundance of 25 fish (aggregation rate = 0.50) in relation to the probability of capture. Shown is the effect of fish occupying different proportions of response area (37.5 ha and 18.75 ha), and whether the sampling buffer was large or small. Results are shown against the base model results in solid black.

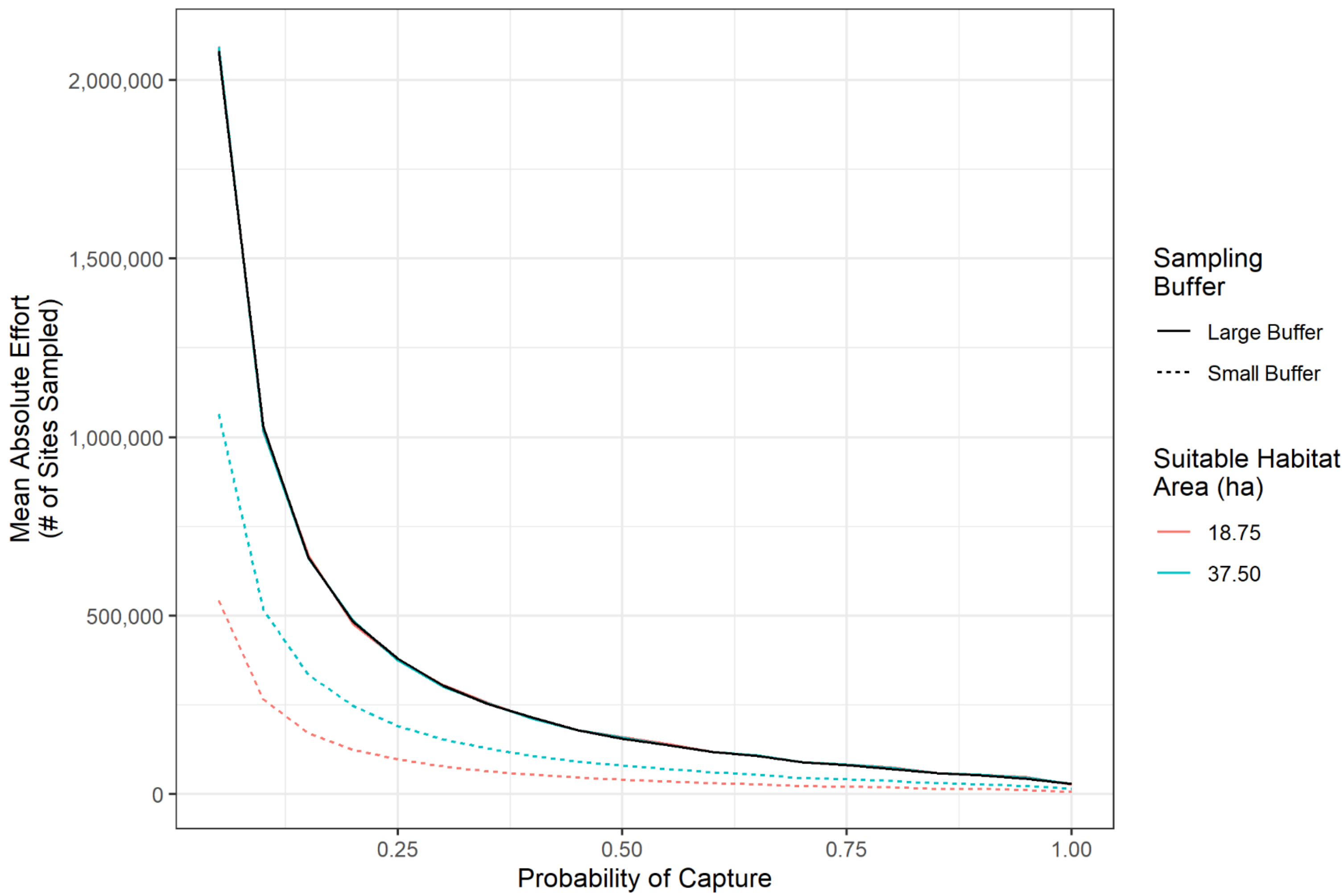

Figure 15. Mean absolute effort (# of sites) needed to locally remove 25 fish (aggregation rate = 0.50) in relation to the probability of capture, with fish occupying different proportions of response area (37.5 ha and 18.75 ha), and whether the sampling buffer was large or small. These results are compared to the base model results in solid black.

Repeat Sampling

The inclusion of the repeat sampling scheme following the capture of a fish at a site only affected the effort required for local removal. The influence of repeat sampling had a greater effect on scenarios with low to moderate probability of capture (Figure 16), higher aggregation behaviour (Figure 17), and larger fish abundances (Figure 18). Scenarios with a high probability of capture (> 0.70) did not change substantially across resampling rates as the majority, if not all, fish occupying a site would be captured during the first sampling effort (here, resampling resulted in no additional fish captured). This was seen with a probability of capture of 0.70 where the mean relative effort to locally remove fish ranged from 0.53 to 2.96 passes of the response area for repeat sampling scenarios compared to a range of 39.44 to 70.60 passes of the response area when probability of capture was 0.05. In addition, repeat sampling decreased effort as fish density at a site increased (i.e., high aggregation rates and high abundances within a given response area size). For example, when probability of capture was 0.05 and five sampling events occurred per site following detection, mean absolute effort of 39.37 passes of the response area was required for local removal when aggregation rate was 1.00 and 59.26 passes of the response area was needed when aggregation rate was 0.75 (compared to a base value of ~ 70 passes with one sampling event per site). Finally, the influence of repeat sampling on the effort required for local removal was greater at higher abundances. For example, compared to the base model, conducting five sampling events resulted in, on average, 27.96 fewer passes of the response area for local removal when probability of capture was 0.05 and abundance was 20 fish (i.e., 38.12 passes required), and 31.23 fewer passes for local removal when abundance was 25 fish (i.e., 39.37 passes required).

Fish Avoidance

The ability of fish to avoid sampling crews and move to alternative sites prior to sampling resulted in increased effort for detection as well as local removal (Figure 19 and Figure 20, respectively); however, the relationship between avoidance and effort was nonlinear. For example, the mean relative effort required for detection increased with avoidance from 0.56 passes (avoidance = 0.00) to 0.90 passes (avoidance = 0.50) and 1.53 passes (avoidance = 0.75; all situations with probability of capture of 0.05 and 25 fish present). Similarly, the mean absolute effort to locally remove 25 fish increased from 69.55 passes (avoidance = 0.00) to 106.02 passes (avoidance = 0.50) and 178.82 passes (avoidance = 0.75; assumes probability of capture of 0.05).

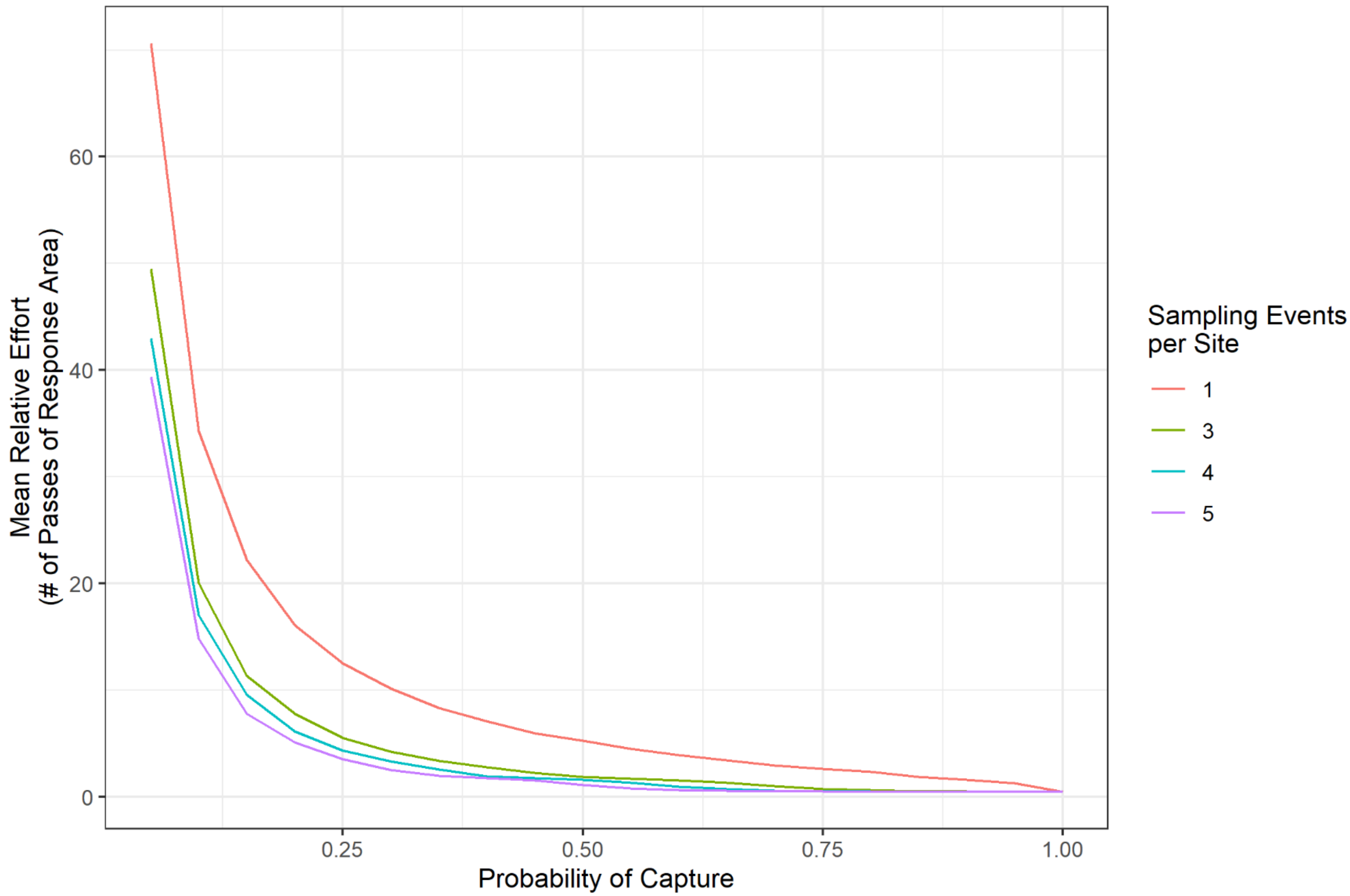

Figure 16. Mean relative effort (# of passes) required for local removal in relation to the probability of capture and four repeat sampling schemes (1, 3, 4, and 5 sampling events in total per site where initial detection occurred). Simulations were based on an abundance of 25 fish with an aggregation rate of 1.00.

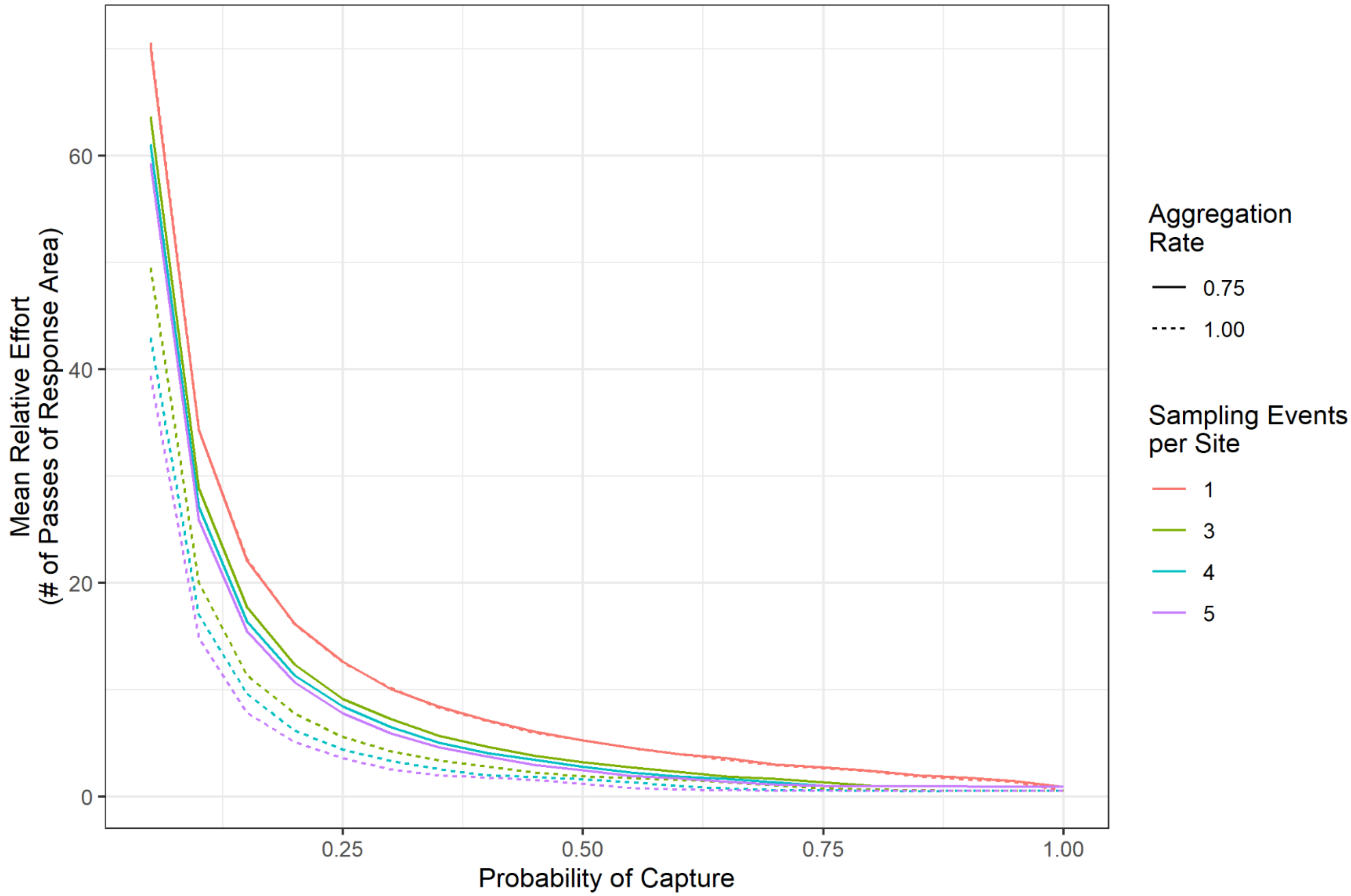

Figure 17. Mean relative effort (# of passes) needed to locally remove 25 fish in relation to the probability of capture, with multiple repeat sampling schemes (1, 3, 4, and 5 sampling events in total per site where initial detection occurred), and whether fish aggregation rate was 0.75 or 1.00.

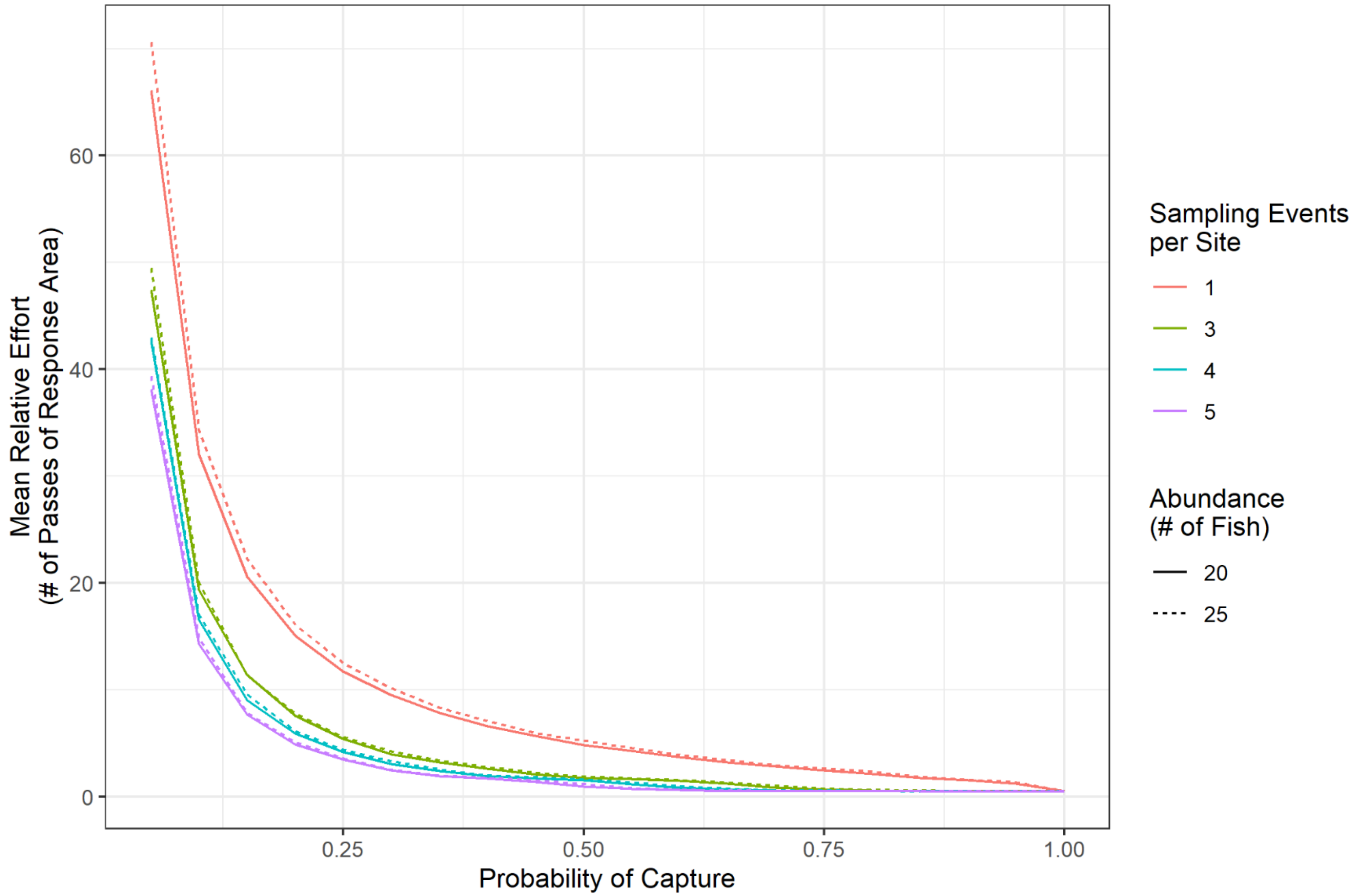

Figure 18. Mean relative effort (# of passes) needed to locally remove 20 or 25 fish in relation to the probability of capture, with multiple repeat sampling schemes (1, 3, 4, and 5 sampling events in total per site where initial detection occurred). Simulations were based on an aggregation rate of 1.00.

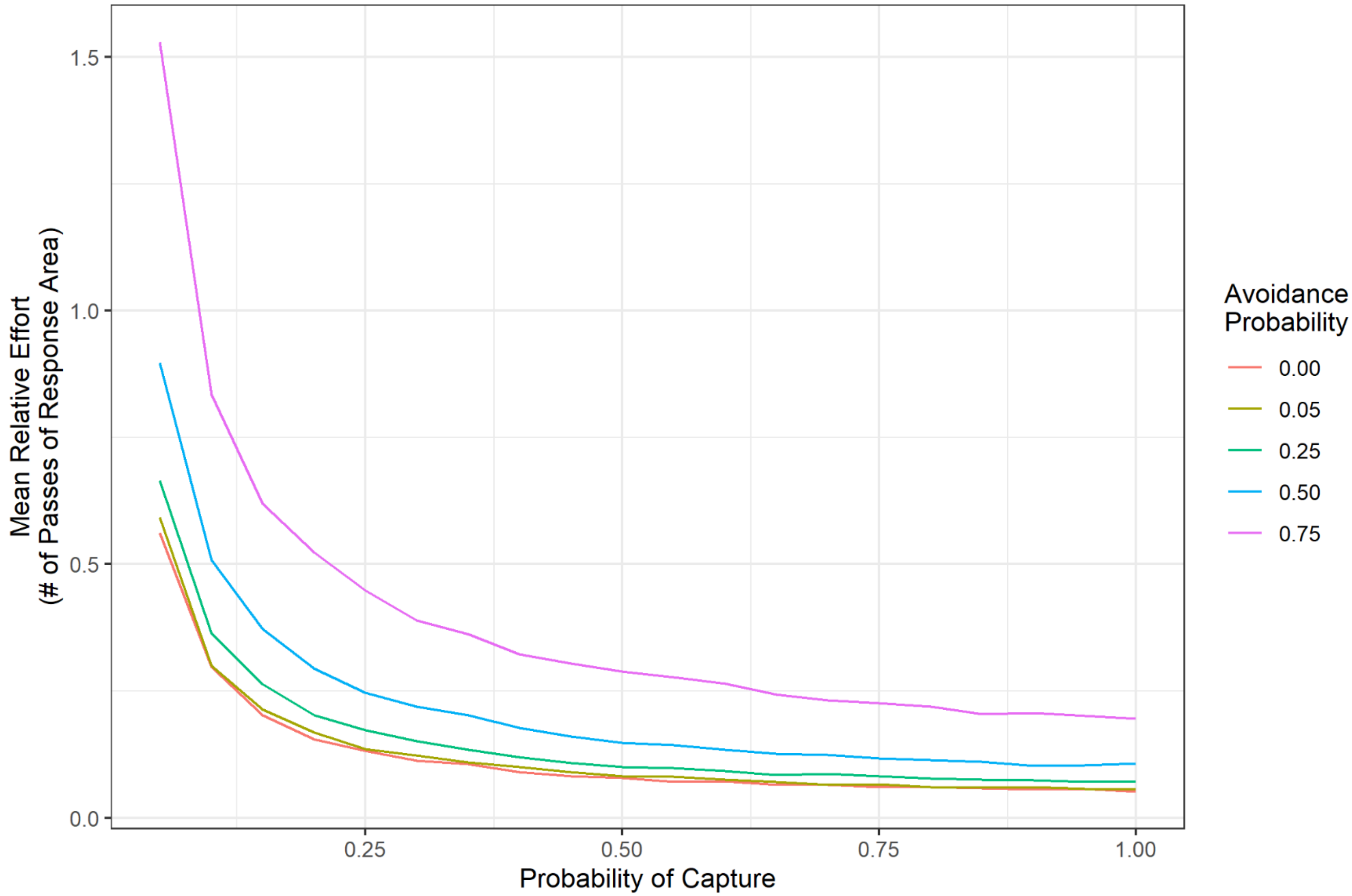

Figure 19. Mean relative effort (# of passes) required for detection in relation to the probability of capture and five avoidance scenarios (i.e., 0.00, 0.05, 0.25, 0.50, and 0.75). Simulations were based on an abundance of 25 fish with an aggregation rate of 0.50.

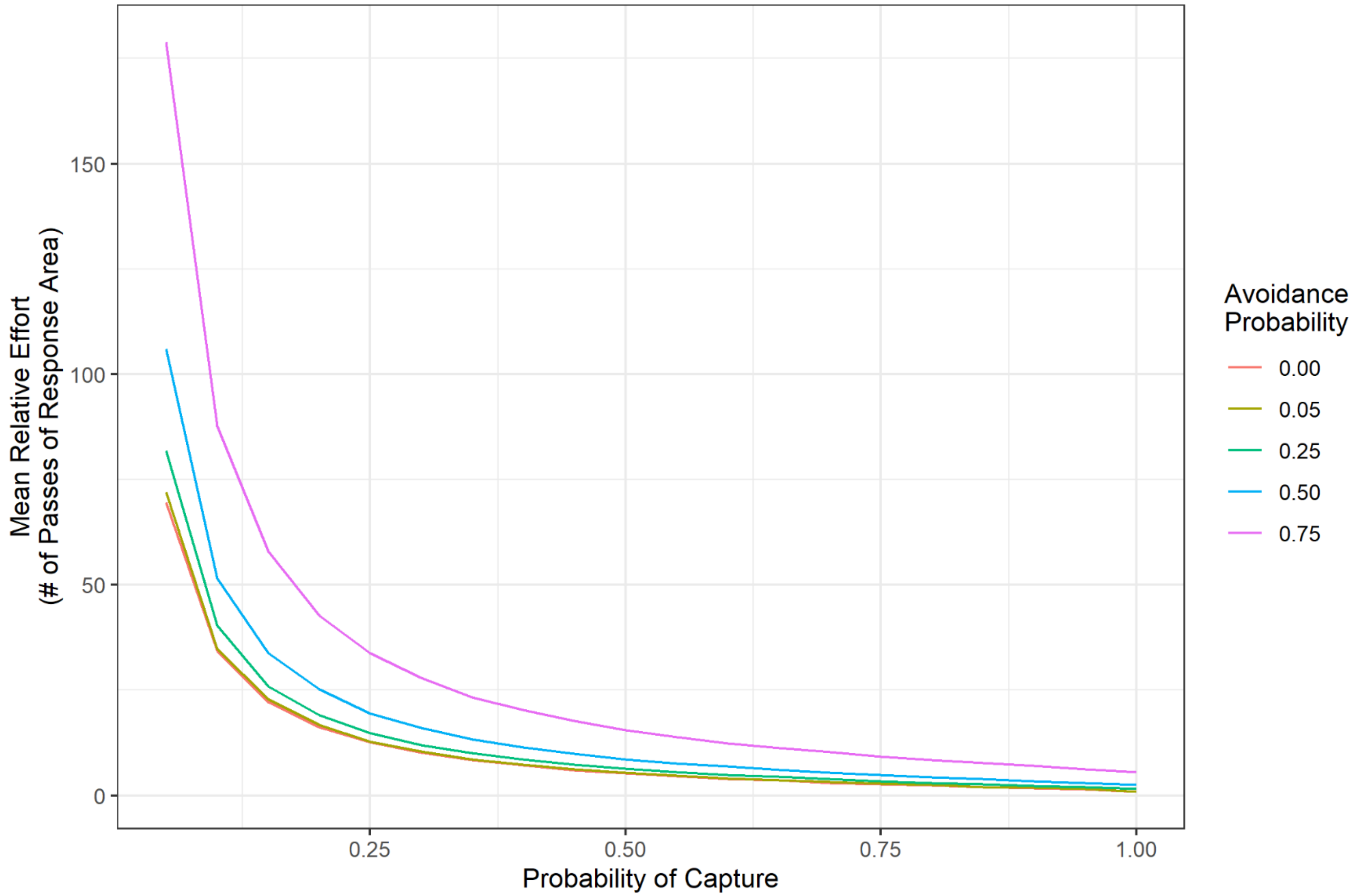

Figure 20. Mean relative effort (# of passes) required for local removal in relation to the probability of capture and five avoidance scenarios (i.e., 0.00, 0.05, 0.25, 0.50, and 0.75). Simulations were based on an abundance of 25 fish with an aggregation rate of 0.50.

Alternative Scenario Synthesis

Based on the alternative scenarios, the following can be concluded about response area, sampling scheme, and fish avoidance. First, the size of the response area had no effect on the relative effort (measured as number of passes of the area) required for detection or local removal. This indicates that the relative results of the simulations are scalable. Total effort, however, scaled with the size of the response area, indicating that the number of sites required to detect or remove Asian carps will be greater in larger response areas. Second, the sampling scheme (systematic versus random, informed, or repeat sampling) influenced the effort required for detection and local removal. Random sampling (with replacement) had a small influence on the effort required for detection and local removal when the probability of capture was low, but required more effort when the probability of capture was high. There was an interaction between aggregation and random sampling, with random sampling requiring more effort under high aggregation rates. In no situation did random sampling perform better than systematic sampling. Informed sampling reduced absolute effort required for both detection and local removal, with the magnitude of the effort reduction proportional to the reduction in habitat area to be sampled. Repeat sampling reduced the effort required for local removal, but not detection, when the probability of capture was low to moderate, under higher aggregation rates, and when Asian carp abundances were higher. Finally, the potential for Asian carps to move within the response area increased the effort required for both detection and local removal. The more likely the fish are to avoid strike teams, the greater the effort required.

SENSITIVITY ANALYSIS

The effort required for detection and local removal varied in relation to sampling scheme, response area, and aggregation and avoidance behaviour across each of the four quadrants (low probability of capture and abundance through high probability of capture and abundance; Figure 21 and Figure 22). When the probability of capture was low (i.e., 0.05), informed sampling (small buffer) resulted in the greatest change in the effort required for detection (whether at low or high abundance), with a relative decrease in effort of 50% (i.e., an absolute decrease of 2.31 passes; Figure 21a) and 48% (i.e., an absolute decrease of 0.27 passes; Figure 21c), respectively. Although informed sampling resulted in the largest and most consistent decreases in the effort required for detection across abundance and probability of capture values (Figure 21), aggregation behaviour led to the greatest increases in effort required for detection when abundance was 25 fish (with a relative increase of 65% and a corresponding absolute increase of 0.04 passes; Figure 21d). It is important to note that although aggregation had the greatest influence (as increased effort required for detection) when abundance was 25 fish, the absolute difference between this scenario and the base scenario, was relatively small (~ 1,000 sites) compared to the difference between the response area size scenario and the base scenario when abundance was 3 fish (~ 8,000 sites).

Similar to detection, local removal was sensitive to sampling scheme, response area, and aggregation and avoidance behaviour. Informed sampling (small buffer) had the greatest influence on local removal, decreasing relative effort by 49% when the probability of capture was low (i.e., 0.05) and abundance was 3 fish (absolute effort decrease of 15.25 passes; Figure 22a) and 25 fish (absolute effort decrease of 33.96 passes; Figure 22c). Informed sampling decreased relative effort for local removal by 48% when the probability of capture was high (i.e., 0.70) and abundance was 3 fish (absolute effort decrease of 0.68 passes; Figure 22b). Random sampling (with replacement) had a slightly greater influence on effort required for local removal than informed sampling when probability of capture was high (i.e., 0.70) and abundance was 25 fish (increasing relative effort by 61% and absolute effort by 1.82 passes compared to decreasing relative effort by 49% and absolute effort by 1.46 passes; Figure 22d).

The sensitivity analyses showed that when the probability of capture was low, it is important that sampling be as targeted (i.e., informed) as possible for both detection and local removal. When the probability of capture was high, effort was sensitive to more variables; detection was most sensitive to avoidance and aggregation, while local removal was most sensitive to avoidance and the sampling scheme (i.e., random sampling).

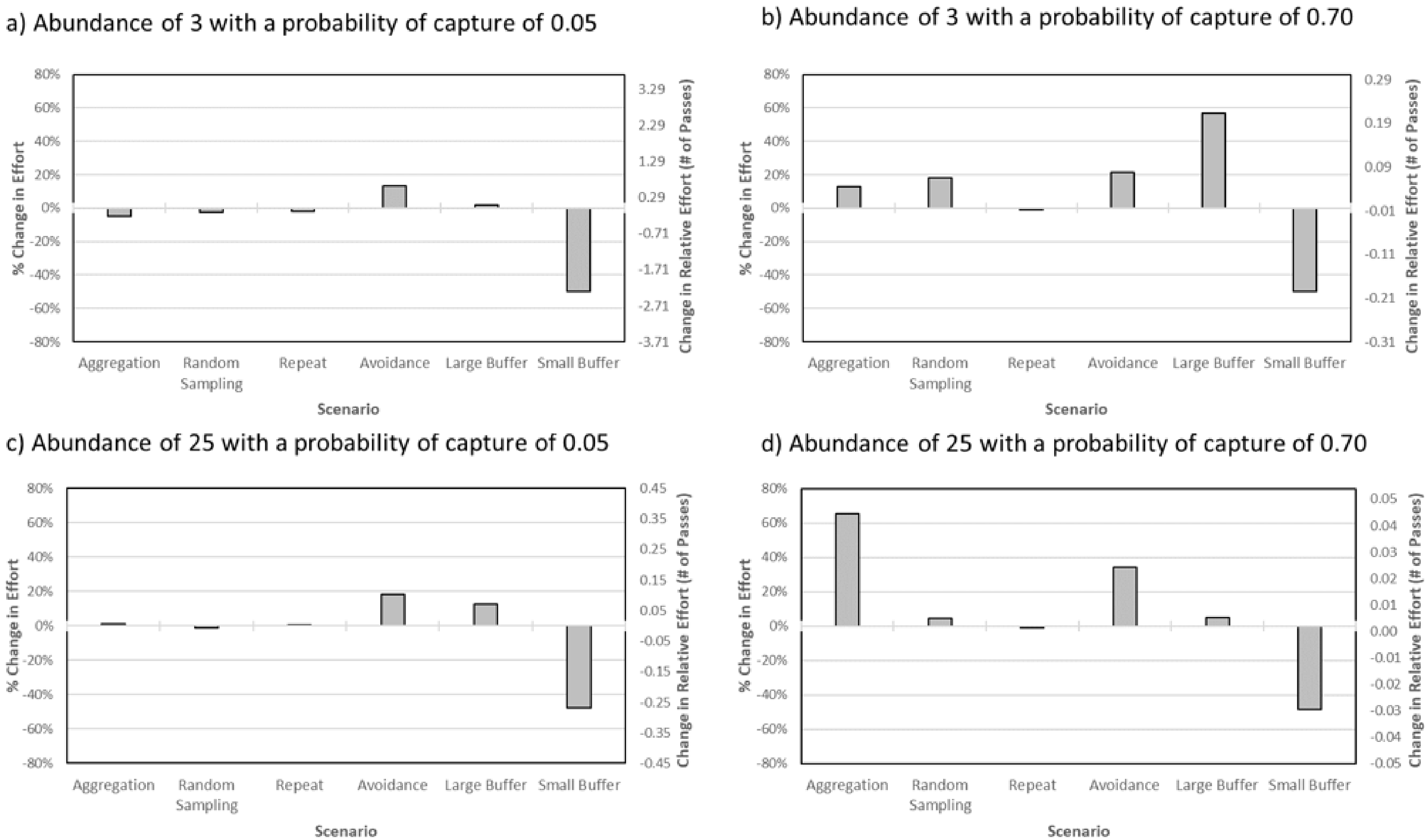

Figure 21. The percent change in effort needed to detect Asian carps when: fish aggregations of 0.75 occurred (aggregation), random sampling was implemented (random sampling), repeat sampling occurred with three samples per site (repeat), fish exhibited avoidance behaviour with a rate of 0.25 (avoidance), crews sampled the entire 75 ha sampling area but only 50% of the response area was suitable for Asian carp (large buffer), and when crews were informed and only sampled the suitable area for Asian carps that composed 50% of the response area (small buffer). Percent changes are in relation to the results of the base model (fish aggregations at 0.50) for the fish abundances and probabilities of capture shown in each panel.

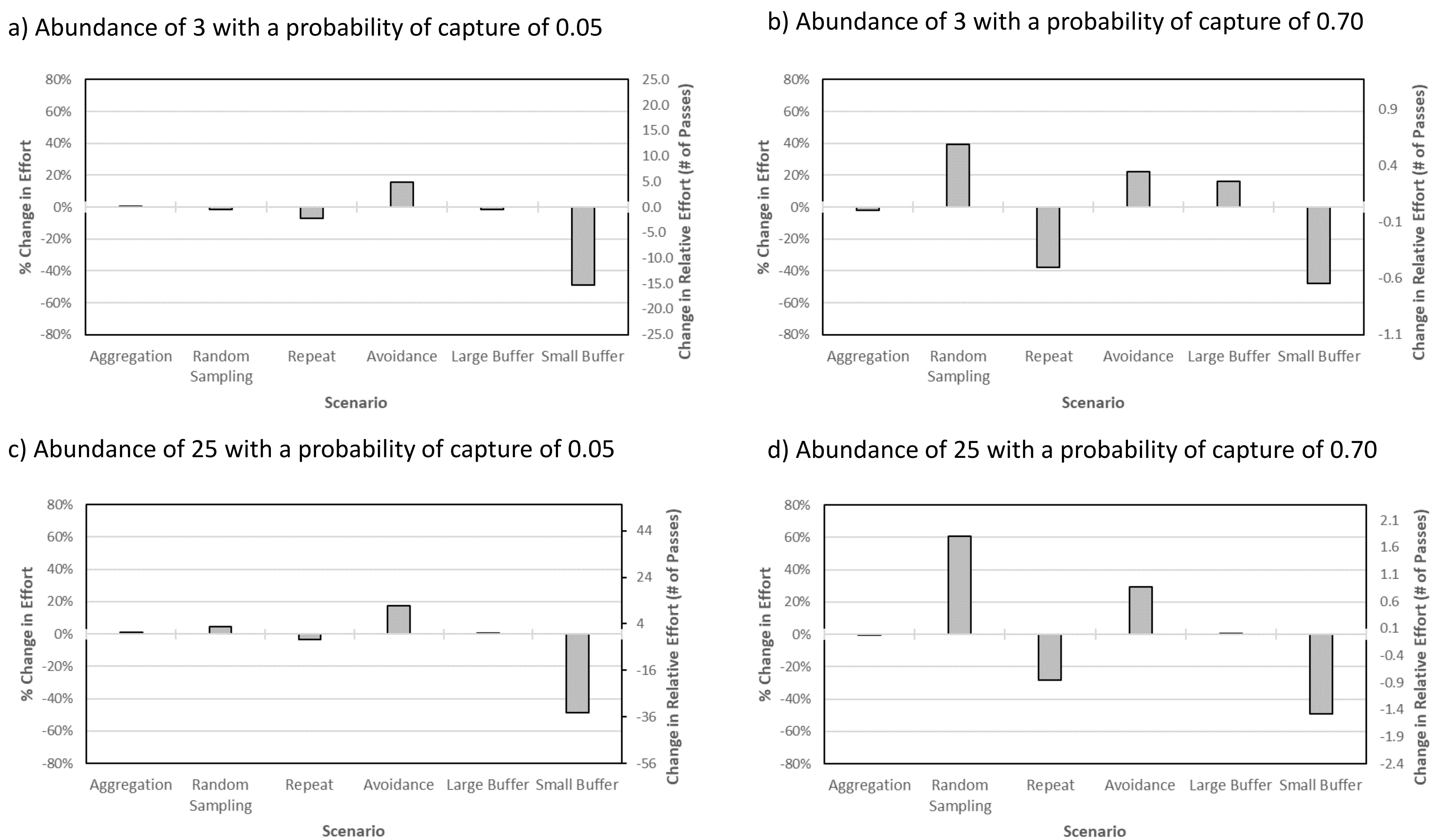

Figure 22. The percent change in effort needed for local removal of Asian carps when: fish aggregations of 0.75 occurred (aggregation), random sampling was implemented (random sampling), repeat sampling occurred with three samples per site (repeat), fish exhibited avoidance behaviour with a rate of 0.25 (avoidance), crews sampled the entire 75 ha sampling area but only 50% of the response area was suitable for Asian carp (large buffer), and when crews were informed and only sampled the suitable area for Asian carps that composed 50% of the response area (small buffer). Percent changes are in relation to the results of the base model (fish aggregations at 0.50) for the fish abundances and probabilities of capture shown in each panel.

DISCUSSION

The analysis demonstrated that although a single sampling pass of the response area can result in the detection and local removal of Asian carps across sampling schemes and literature-supported probability of capture values of 0.05 to 0.70, in most cases, repeat passes of the response area will be required to successfully capture and remove Asian carps. Given that a single pass of a 75 ha response area could require ~ 83 sampling hours (based on 10 seconds/site), the need for multiple passes of the response area presents a challenging task for strike teams. In addition, results demonstrated that passes without catches can be used to predict the probability that a given abundance of Asian carps remains in the response area, though this requires that the probability of capture of the employed gear can be determined. For example, five empty passes would be sufficient to conclude that no Asian carps remained within the response area, unless probability of capture was low (i.e., ≤ 0.25). The results also demonstrated that many of the relative results (# of passes) can be scaled to different response area sizes. Although the absolute magnitude of effort (# of sites) will change as strike teams fish in different response areas, the general conclusions regarding factors that influence relative effort will apply to responses of varying size. Improvements to the response protocols including targeting only suitable habitat for Asian carps within a sampling area (informed sampling) or resampling sites immediately following captures (repeat sampling) can substantially reduce sampling effort; however, resampling is only effective if fish display aggregation behaviour. In addition, fish avoidance substantially increased the effort required for capture and local removal.

Although there are opportunities to reduce the effort required to detect and locally remove Asian carps (i.e., repeat sampling), these approaches are not guaranteed to reduce sampling effort or increase the likelihood of local removal. Repeat sampling substantially reduced the effort needed for local removal when aggregation occurred, but would have no influence when fish aggregation is very low or the probability of capture is very high (> 0.90), which is unlikely given the literature-supported probability of capture values (Table 1). Therefore, if fish aggregation is absent or limited (i.e., aggregation rate ≦ 0.25), implementing a repeat sampling protocol may not decrease the effort needed for local removal.

The sensitivity analysis demonstrated that there are a few factors that have consistent influence on the effort needed for detection or local removal. Informed sampling had the greatest decrease on the effort required for detection and local removal across the range of probability of capture and abundance values, except when the probability of capture was high. Therefore, increased emphasis on sampling preferred habitat provides the best opportunity to reduce response effort when compared with incorporating different sampling schemes (systematic vs. random sampling or repeat sampling following detection).

Given the uncertainty of model parameters used in the simulations (probability of capture, number of fish present, aggregation rate, and fish avoidance rate), it may be worth assuming a worst-case scenario when identifying the effort required for detection and local removal. For detection, the worst-case scenario involved low probability of capture and few carp present, with a high avoidance rate. For local removal, the worst-case scenario involved low probability of capture, with high numbers of carp present and high avoidance rates. Additional analyses should consider the consequences of being wrong about these parameters when implementing sampling schemes.

Several limitations and uncertainties require elaboration. The first limitation is that the probability of capture was assumed to be similar for each individual fish and throughout the response area. Catchability is influenced by numerous factors including habitat and fish size (Table 2), all of which are expected to vary during a response; this will influence the probability of capture. For example, the fish within a response area may vary in size, each with varying probabilities of capture due to size-based effects. Individual probabilities of capture could vary further if fish occupy sites of different physical structure (e.g., water depth, substrate, vegetation, etc.). A small number of passes may be sufficient to capture a large Asian carp in habitat lacking complex structure; however, multiple passes may be required to capture smaller individuals or individuals in complex habitat. Therefore, the effort estimates at moderate to low fish density (i.e., moderate to high aggregation rates with moderate to low abundances) may be overly optimistic particularly in more complex habitat. In addition, fish density may influence the probability of capture as factors including gear saturation may decrease catchability (Schoenebeck and Hansen 2005) and thus, the individual capture probability at low aggregation rates may be higher than the individual capture probability at high aggregation. Gear saturation for electrofishing is likely substantially greater than for the fish densities incorporated in this analysis (e.g., Schoenebeck and Hansen 2005); however, this may pose a greater issue for net-based sampling (Portt et al. 2006).

The results presented in this analysis provide simplified capture probabilities, which should be considered when evaluating the effort estimates for capture gears employed in the field. Another limitation is that the potential emigration of Asian carps from the response area was not incorporated. Some response locations visited by DFO strike teams were relatively confined, where emigration from the response area was unlikely (e.g., Lake Gibson and Jordan Harbour); however, other locations (e.g., Toronto Islands) had few physical confinements, potentially allowing Asian carps to leave the response area and thus avoid capture. Telemetry data of Grass Carp within the Great Lakes suggests that, although it can exhibit large-scale movement, the probability of such movement is low (Harris et al. 2021 supplemented with additional data, T. Brenden, Michigan State University, unpublished data; See Appendix C); however, these data lacked the ability to document small-scale movements (< 100 m) that may be sufficient for individual fish to vacate response areas. Although emigration from the response area was not quantified, it is a realistic situation that would influence the ability of strike teams to capture all available fish. The potential for emigration likely increases with time since first detection, which is of note given that some scenarios required multiple, if not 100's, of passes of the response area to successfully locally remove fish. The potential for fish to leave the response area prior to detection by strike teams warrants further study.

An additional limitation is that it was assumed that informed sampling can accurately determine, *a priori*, the sites containing Asian carps based on external factors (e.g., habitat condition). Some habitat preferences have been identified for Asian carps (e.g., Grass Carp preferring shallow, vegetated habitat [Cudmore and Mandrak 2004] as well as habitat with complex structure including large woody debris [Weberg et al. 2020]); however, many of these studies have been conducted outside of the Great Lakes basin. Invasive species may display novel behaviour (including habitat preference) in new environments (e.g., Kolar et al. 2007, Cucherousset et al. 2012, Liu et al. 2020) and, thus, Asian carps' habitat preferences within the basin may differ from what is documented in the literature. Although the results demonstrate the value of informed sampling, such sampling requires accurate identification of occupied sites, otherwise fish remaining will be undetected.

The models did not directly evaluate the potential benefit of herding fish, which may occur via multi-gear sampling. During Asian carp responses, strike teams often deploy trammel nets as well as boat electrofishing within the response area. Asian carps have been captured using both methods; however, the captures in trammel nets can increase when boat electrofishing is used to herd fish towards nets (Butler et al. 2019). Although the influence of boat-based herding to nets was not explicitly evaluated, the benefit of herding may be represented in the models as either high probability of capture values (e.g., near the literature-supported catchability upper limit of 0.70) or smaller response areas. Herding could also be used to reduce effort required for local removal if fish that are initially dispersed throughout a response area can be herded into a small portion of the response area. If fish remained trapped within this smaller area, the expected effort required would be similar to reducing the response area size. Despite the potential benefits of herding to reduce response effort, herding could also have the unintended effect of increasing fish movement rates that could lead to fish avoidance or possibly, emigration from the response area.

It is important to recognize that the results of this analysis were not constrained to factors specific to Asian carps. Therefore, results are transferable to other species of interest (invasive or otherwise). Applying the results to other species requires the suitability of the underlying parameter values (fish abundance, probability of capture, avoidance and aggregation behaviour) to be evaluated in the context of each species of interest.

The simulations demonstrated that multiple passes of the response area will likely be needed to capture and locally remove Asian carps within the literature-supported probability of capture range of 0.05-0.70 for Asian carps based on electrofishing (Table 1). However, it remains unknown how the probability of capture of trammel nets compares to electrofishing or a joint approach involving both gears concurrently. Some evidence suggests that trammel net captures can be comparable to or even greater than electrofishing (Herbst et al. 2021). Although most captures by DFO responses have occurred with trammel nets (e.g., Lake Gibson), other studies have shown a greater number of Grass Carp captured using electrofishing compared to netting (i.e., gill netting and commercial seine netting) (Herbst et al. 2021). In most cases, extensive effort has been required to capture Asian carps and other carp species. For example, previous sampling in seven areas where eDNA was detected for Grass Carp resulted in two captures after 96 hours of electrofishing while multiple netting sets (gillnet and commercial seines) yielded no captured carps (Herbst et al. 2021). Crucian Carp have evaded seine, gillnet, and trap net captures while only being successfully captured using electrofishing, while Common Carp have been successfully captured by all methods (Barthelmes and Brämick 2003). Gillnetting has resulted in higher catch-per-unit-effort (CPUE) than splash-netting for Common Carp; however, boat electrofishing during the same period caught a substantially greater number of carp (Norris et al. 2014). Electrofishing can have substantially higher catch rates for Common Carp compared to other techniques including angling, fyke netting, seine, and longline (Norris et al. 2014) and can result in a substantially greater CPUE compared to gillnets in lagoon habitat (Norris et al. 2014).

Overall, the results demonstrated that substantial effort will be required for local removal when probability of capture is low (< 0.25), particularly when abundance is moderate to high (>15 fish). The estimated effort required for local removal is consistent with the literature. For example, three pass removal sampling has been deemed ineffective for the local removal of other carp species including the Prussian Carp (Card et al. 2020). Eradication attempts without the use of chemical control methods can take years, if not decades, of annual removal sampling to successfully eradicate small fish populations within an area (e.g., trout; Bosch et al. 2019), though chemical control methods (e.g., rotenone) are often required (e.g., Brook Trout; Banish et al. 2019). Therefore, if the local removal of Asian carps remains a core objective, extensive effort or techniques to improve probability of capture will be required. Given the extensive effort needed for local removal (which may be unattainable due to logistical constraints), incorporating knowledge of the relationship between fish abundance and species establishment may help to determine the critical abundance of fish remaining that would be unlikely to establish a reproducing population. Simulation models have evaluated the potential for successful Asian carp establishment with relatively few propagules (< 25 adults; Cuddington et al. 2014, Smyth and Drake 2021), but as more individuals are removed from a response area, the probability of establishment decreases (Cassey et al. 2018). In the absence of this approach, the factors outlined above (improvements to probability of capture and informed sampling) provide the best opportunity to improve detection and the efficacy of local removal.

Although this analysis has estimated the effort required for detection and local removal of Asian carps, these estimates can be refined through future study and experimentation. One of the greatest uncertainties concerns the probability of capture for Asian carps. Field-based depletion studies or repeated sampling efforts with block nets could help refine the range of probability of capture values considered in this report. In addition, other uncertainties surrounding fish movement including emigration and avoidance behaviour could be examined through small scale movement studies in which fish movement during response and their aggregation potential is estimated. In addition, better understanding the habitat preferences of Asian carps in the Great Lakes basin would improve the identification of suitable habitat during response activities, which would allow the benefits of informed sampling to be realized. Each of these potential studies could substantially reduce uncertainties around response effort required for detection and local removal.

ACKNOWLEDGEMENTS

We acknowledge the participants of the Canadian Science Advisory Secretariat peer review meeting, whose comments substantially improved this research document. We also thank T. Brenden for providing Grass Carp telemetry data to inform potential movement of Asian carps. We are grateful to D. Marson and J. Colm for providing Asian Carp Response Program data and providing details on previous response efforts.

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APPENDIX A. GLOSSARY OF KEY TERMS

Catchability - The probability that fish within a site are captured during a sampling event per unit of effort or fishing intensity

Detection – The effort required to capture one fish following the implementation of a response.

Local removal – The removal of all individual Asian carps present within a response area.

Probability of capture – The probability that a fish within a site will be captured following a single sampling event.

Response area – The defined area which is used to frame the spatial scale of response activities following detection.

Sampling area – The defined area within the response area where strike teams sample for Asian carps.

Site – A 5 x 5 m square within the sampling area that is sampled by strike teams that fish may occupy.

APPENDIX B. SENSITIVITY RESULTS

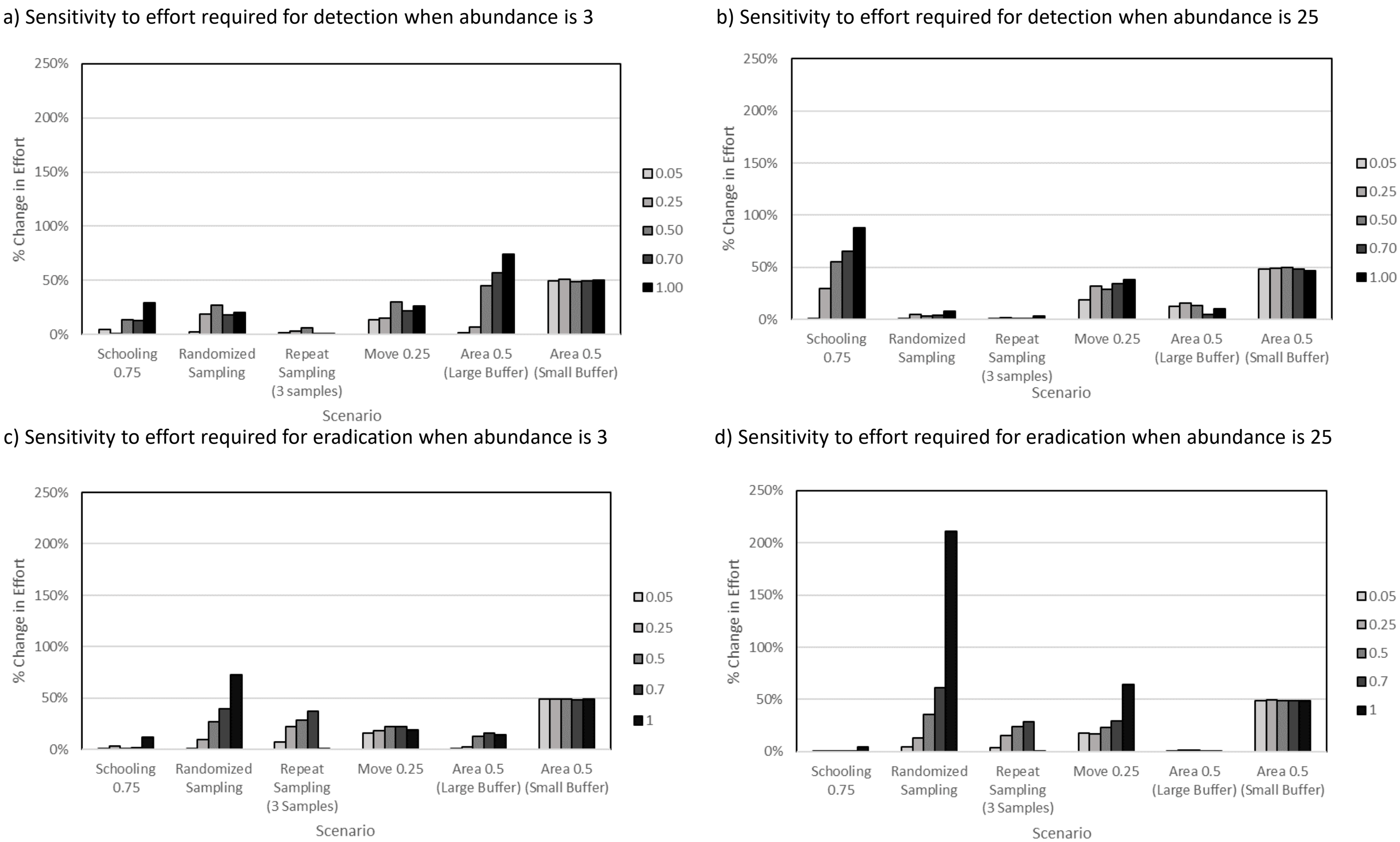

Figure B1. The percent change in effort needed for detection (panels a and b) and local removal (panels b and c) of Asian carps across probabilities of capture when: fish aggregations of 0.75 occurred (aggregation), random sampling was implemented (random sampling), repeat sampling occurred with three samples per site (repeat), fish exhibited avoidance behaviour with a rate of 0.25 (avoidance), crews sampled the entire 75 ha sampling area but only 50% of the response area was suitable for Asian carps (large buffer), and when crews were informed and only sampled the suitable area for Asian carps that composed 50% of the response area (small buffer). Percent changes are in relation to the results of the base model (fish aggregations at 0.5) for fish abundances of 3 fish (panels a and c) and 25 fish (panels b and d) are shown.

APPENDIX C. GRASS CARP TELEMETRY SUMMARY

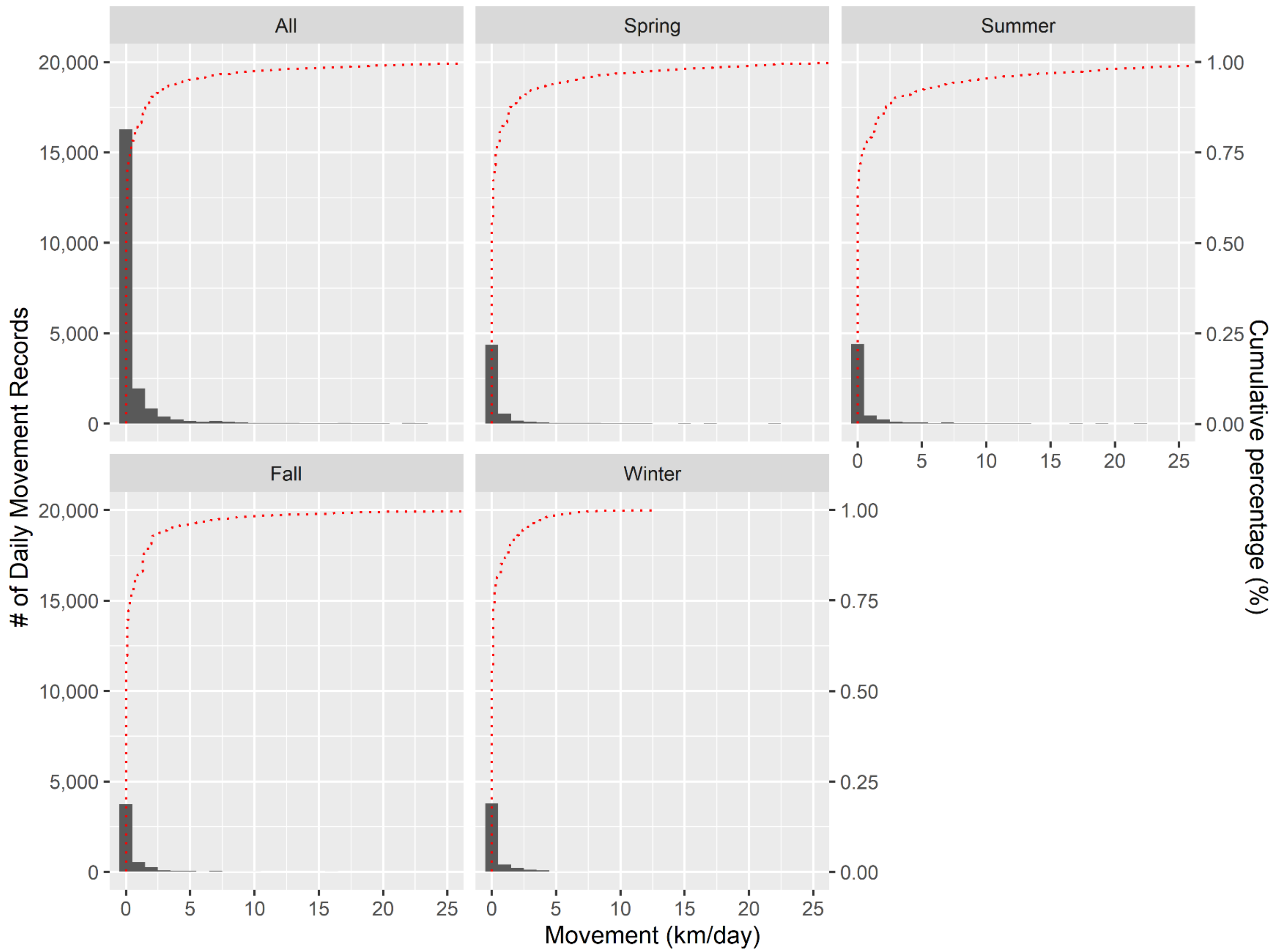

Figure C1. Frequency and cumulative percentage (%) of daily Grass Carp movement (km/day) from telemetry work conducted from October 2014 to March 2020 (Harris et al. 2021 and T. Brenden, Michigan State University, unpublished data).

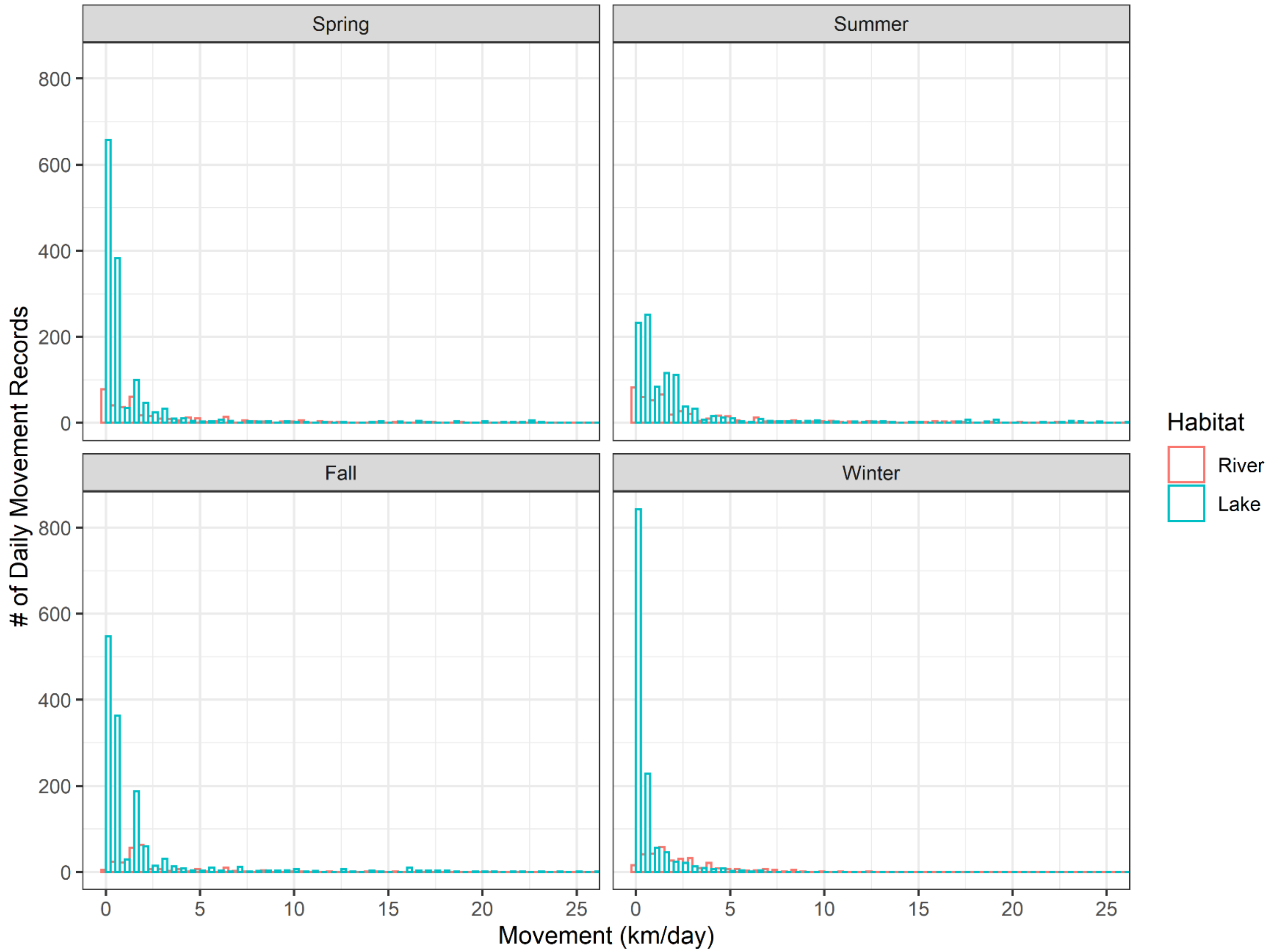

Figure C2. Frequency of daily Grass Carp movement (km/day) from telemetry work conducted from October 2014 to March 2020 with zero movement removed across all seasons and habitats sampled (Harris et al. 2021 and T. Brenden, Michigan State University, unpublished data).