Simulation Model Results to Estimate the Effort Required to Detect Asian Carps in the Laurentian Great Lakes Basin

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Simulation models were used to determine the relationships between species abundance, the probability of capture, and response effort as part of a Canadian Science Advisory Secretariat (CSAS) process to examine the response effort required to detect and remove Asian carps in the Great Lakes basin. Simulation models incorporated differences in fish aggregation behaviours, response area sizes, sampling schemes (i.e., systematic, randomized, repeat, and informed sampling), and fish avoidance behaviours to determine their influence on effort required for detection and local removal. This data report presents detailed results of the simulation models, which are fully described in the related CSAS Research Document. The mean relative effort to detect a single fish ranged from 0.052 to 13.484 passes of the 75 ha response area given: abundances from 1 to 25 fish, probabilities of capture from 0.05 to 1.00, and an assumed base model involving systematic sampling. 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 0.504 to 69.545 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. Simulation outputs across fish aggregation rates, response area sizes, sampling schemes (i.e., systematic, randomized, repeat, and informed sampling), and fish avoidance rates are also provided.

RÉSUMÉ

Smyth, E.R.B., Koops, M.A., and Drake, D.A.R. 2021. Simulation Model Results to Estimate the Effort Required to Detect Asian Carps in the Laurentian Great Lakes Basin. Can. Data Rep. Fish. Aquat. Sci. 1345: vii + 20 p.

On a utilisé des modèles de simulation pour déterminer les relations entre l'abondance des espèces, la probabilité de capture et l'effort d'intervention dans le cadre du processus du Secrétariat canadien des avis scientifiques (SCAS) visant à examiner l'effort d'intervention nécessaire pour détecter et retirer les carpes asiatiques du bassin des Grands Lacs. On a intégré aux modèles de simulation des différences concernant le comportement de regroupement des carpes, la taille des zones d'intervention, la méthode d'échantillonnage (c.-à-d., échantillonnage systématique, randomisé, répété ou éclairé) et le comportement d'évitement des carpes afin de déterminer l'incidence de ces paramètres sur l'effort requis pour la détection d'individus et leur retrait à l'échelle locale. Le présent rapport de données présente les résultats détaillés des modèles de simulation, qui sont entièrement décrits dans le document de recherche du SCAS connexe. L'effort relatif moyen pour la détection d'un seul individu variait de 0,052 à 13,484 passages dans la zone d'intervention donnée de 75 ha. L'abondance variait de 1 à 25 individus et la probabilité de capture, de 0,05 à 1,00. On a présumé que le modèle de référence était fondé sur un échantillonnage systématique. L'effort d'intervention requis pour la détection a diminué de façon non linéaire lorsque l'abondance des individus ou la probabilité de capture augmentait. L'effort relatif moyen requis pour le retrait d'individus à l'échelle locale variait de 0,504 à 69,545 passages dans la zone d'intervention; on a observé une relation non linéaire semblable lorsque de faibles augmentations de la probabilité de capture au-delà de 0,05 ont entraîné des baisses importantes de l'effort requis pour le retrait des carpes à l'échelle locale. Le rapport présente également les résultats de simulation pour l'ensemble des taux de regroupement des individus, des tailles de la zone d'intervention, des méthodes d'échantillonnage (c.-à-d., échantillonnage systématique, randomisé, répété et éclairé) et des taux d'évitement des carpes.

INTRODUCTION

Early detection and rapid response (EDRR) is one approach for preventing or slowing species invasions (Reaser et al. 2020). 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 potential invasion of Asian carp species [i.e., Grass Carp (*Ctenopharyngodon idella*), Bighead Carp (*Hypophthalmichthys nobilis*), Silver Carp (*H. molitrix*), and Black Carp (*Mylopharyngodon piceus*)].

Data contained in this report were assembled to support a Canadian Science Advisory Secretariat (CSAS) process aimed at evaluating the sampling effort required to detect and locally remove Asian carps (Smyth et al. 2021) in the Laurentian Great Lakes basin. Data were generated from simulation models that examined multiple sampling schemes (systematic vs. randomized sampling, informed sampling, and repeated sampling following detection), while considering uncertainties associated with the size of the response area, fish abundance within the response area, the probability of capture, as well as fish aggregation and avoidance behaviour. This data report provides descriptions of the results of the simulation models, which were used to inform the CSAS Research Document (Smyth et al. 2021).

METHODS

Simulation models were used to calculate the effort required for the detection and local removal of Asian carps within the response area across different population abundances and probability of capture rates, along with the effect of different sampling schemes, sizes of the response area, and estimates of fish aggregation or avoidance within the fished area. Full methods can be found in the CSAS Research Document by Smyth et al. (2021).

BASE MODEL

The base model was developed on a 173 x 173 square matrix to represent a ~ 75 ha response area with each grid cell (hereby referred to as a site) as 0.0025 ha (25 m^2). Multiple fish abundances within the response area were used (i.e., 1, 3, 5, 7, 10, 15, 20, and 25 fish) to determine how effort for detection and local removal may vary across fish abundance. Fish were randomly assigned to sites throughout the response area matrix where they would remain during the simulation; however, the probability that a fish would be assigned to an occupied site was based on the fish aggregation rate. Five aggregation rates were examined (i.e., 0.00, 0.25, 0.50, 0.75, 1.00), which reflect the probability that an individual fish would be assigned to sites inhabited by other fish, to determine how fish aggregation may influence effort required for detection and local removal. 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. When the strike team sampled an occupied site, the capture of each individual Asian carp was based on the probability of capture. Multiple probabilities of capture were examined using simulation models (i.e., 0.05 to 1.00 with 0.05 increments).

Simulation models were run for 5,000 iterations for each fish abundance, aggregation, and probability of capture value (hereby referred to as a scenario). For each iteration, the strike team would systematically sample each site of the 29,929 sites within the response area matrix. Once a fish was captured, the number of sites sampled until capture was recorded. Sampling continued until all fish were captured and removed from the response area. Effort needed for detection reflects the number of sites or passes of the entire response area (29,929 sites) sampled until the first fish was captured in each iteration, while effort needed for local removal

reflects the number of sites or passes of the response area sampled until the last fish was captured for each iteration.

ALTERNATIVE SCENARIOS

In addition to the base model, alternative sizes of the response area, sampling schemes (systematic, randomized, repeated, and informed sampling), and fish avoidance rates within the response area were incorporated to determine their influence on response efficacy. Further details on how each of these alternative scenarios were developed are provided in Smyth et al. (2021). Alternative response area sizes were examined by calculating detection and local removal effort when the response area was ~ 37.50 ha (50% of base model response area) and ~ 18.75 ha (25% of base model response area). The randomized sampling scheme was examined by randomly sampling sites (with replacement) within a response area. The repeated sampling scheme considered a situation where strike teams will immediately resample a site following the capture of a single fish. Multiple repeat sampling rates were considered (i.e., 3, 4, and 5 total sampling events per site following an initial detection at a site). The informed sampling scheme considered a situation where only a portion of the response area would be suitable for Asian carps and crews sampled within this reduced area of suitable habitat. Asian carps were randomly assigned to sites within 50% (37.50 ha) or 25% (18.75 ha) of the response areas and crews either sampled the entire 75.00 ha response area ("large buffer") or the reduced habitat areas ("small buffer"). Fish avoidance was incorporated by considering multiple probabilities (i.e., 0.05, 0.25, 0.50, and 0.75) that fish may depart a site immediately prior to sampling and be randomly assigned to a different site within the response area.

RESULTS

The base model results of the effort required for detection (Table 1) and local removal (Table 2) were calculated, as well as the influence of fish avoidance on the effort required for detection and local removal (*Table 3* and Table 4, respectively). The relative (# of passes of the response area) and absolute effort (# of sites sampled) required for detection (*Table 5* and *Table 6*) and local removal (*Table 7* and *Table 8*) was calculated across response area sizes. The influence of a randomized sampling scheme on the effort needed for detection (*Table 9*) and local removal (*Table 10*) was evaluated. Also evaluated was the influence of informed sampling on the effort needed for detection (*Table 11*), local removal (*Table 12*) and the influence of repeated sampling on the relative effort needed for local removal (*Table 13*), as well as the sensitivity of the results to fish aggregation and abundance (*Table 14* and *Table 15*, respectively). The influence of fish avoidance within the response area on relative effort required for detection (*Table 16*) and local removal (*Table 17*) was also calculated. To keep values standardized, the pass effort results are presented to two decimal points; however, this level of precision may be an overestimate given the nature of the simulation models.

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Table 1. Mean relative effort (# of passes) required for detection of a single Asian carp individual across multiple probability of capture values and fish abundances 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.

Probability of Capture	**1 Fish**	**3 Fish**	**5 Fish**	**7 Fish**	**10 Fish**	**15 Fish**	**20 Fish**	**25 Fish**
0.05	13.48	4.64	2.72	1.97	1.41	0.91	0.69	0.56
0.10	6.55	2.11	1.34	0.96	0.70	0.47	0.36	0.30
0.15	4.31	1.49	0.86	0.65	0.47	0.34	0.25	0.20
0.20	3.24	1.02	0.69	0.51	0.38	0.26	0.20	0.16
0.25	2.42	0.86	0.57	0.43	0.32	0.22	0.16	0.13
0.30	2.01	0.71	0.49	0.38	0.27	0.18	0.14	0.11
0.35	1.65	0.62	0.41	0.32	0.24	0.16	0.13	0.11
0.40	1.38	0.55	0.38	0.29	0.21	0.15	0.11	0.09
0.45	1.16	0.53	0.36	0.27	0.19	0.14	0.11	0.08
0.50	1.02	0.46	0.32	0.25	0.18	0.13	0.10	0.08
0.55	0.91	0.45	0.30	0.24	0.17	0.12	0.10	0.07
0.60	0.84	0.43	0.29	0.22	0.17	0.11	0.09	0.07
0.65	0.76	0.41	0.27	0.21	0.16	0.11	0.08	0.07
0.70	0.72	0.38	0.26	0.20	0.15	0.10	0.08	0.07
0.75	0.67	0.36	0.25	0.20	0.14	0.10	0.08	0.06
0.80	0.63	0.36	0.24	0.18	0.14	0.10	0.07	0.06
0.85	0.58	0.33	0.23	0.19	0.13	0.10	0.07	0.06
0.90	0.55	0.33	0.22	0.17	0.13	0.09	0.07	0.06
0.95	0.52	0.32	0.22	0.17	0.11	0.09	0.07	0.06
1.00	0.50	0.30	0.22	0.16	0.12	0.09	0.06	0.05

Table 2. 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.

Probability of Capture	**1 Fish**	**3 Fish**	**5 Fish**	**7 Fish**	**10 Fish**	**15 Fish**	**20 Fish**	**25 Fish**
0.05	13.48	31.25	40.36	46.11	52.09	60.73	66.09	69.55
0.10	6.55	14.80	19.21	22.25	25.73	28.79	31.96	34.39
0.15	4.31	9.66	12.47	14.57	16.54	18.83	20.86	22.16
0.20	3.24	7.04	9.05	10.68	11.97	13.87	15.21	16.14
0.25	2.42	5.58	7.16	8.32	9.44	10.73	11.78	12.70
0.30	2.01	4.52	5.76	6.69	7.63	8.67	9.51	10.19
0.35	1.65	3.68	4.80	5.50	6.28	7.25	7.84	8.46
0.40	1.38	3.10	3.97	4.72	5.26	6.07	6.66	7.16
0.45	1.16	2.74	3.51	3.94	4.61	5.15	5.65	5.99
0.50	1.02	2.28	3.00	3.44	3.95	4.52	4.84	5.22
0.55	0.91	1.99	2.62	2.98	3.46	3.92	4.23	4.58
0.60	0.84	1.80	2.31	2.65	2.99	3.50	3.77	3.95
0.65	0.76	1.60	1.96	2.33	2.68	2.96	3.33	3.58
0.70	0.72	1.41	1.78	1.98	2.34	2.70	2.90	2.99
0.75	0.67	1.23	1.62	1.81	1.97	2.35	2.59	2.75
0.80	0.63	1.00	1.41	1.62	1.82	1.96	2.17	2.38
0.85	0.58	0.90	1.16	1.39	1.61	1.80	1.89	1.96
0.90	0.55	0.83	0.95	1.02	1.34	1.58	1.73	1.79
0.95	0.52	0.76	0.86	0.91	0.96	1.11	1.32	1.47
1.00	0.50	0.70	0.79	0.83	0.88	0.91	0.93	0.95

Table 3. Mean relative effort (# of passes) required for detection of a single Asian carp individual across multiple probability of capture values and aggregation rates (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00), given systematic sampling and an abundance of 25 fish.

Probability of Capture	**Aggregation = 0.00**	**Aggregation = 0.25**	**Aggregation = 0.50**	**Aggregation = 0.75**	**Aggregation = 1.00**
0.05	0.54	0.57	0.56	0.57	0.68
0.10	0.26	0.27	0.30	0.32	0.53
0.15	0.19	0.19	0.20	0.24	0.51
0.20	0.14	0.15	0.16	0.20	0.50
0.25	0.11	0.12	0.13	0.17	0.50
0.30	0.09	0.10	0.11	0.16	0.50
0.35	0.08	0.09	0.11	0.14	0.48
0.40	0.07	0.08	0.09	0.13	0.50
0.45	0.06	0.07	0.08	0.13	0.51
0.50	0.06	0.06	0.08	0.12	0.50
0.55	0.05	0.06	0.07	0.12	0.49
0.60	0.05	0.06	0.07	0.11	0.50
0.65	0.04	0.05	0.07	0.11	0.49
0.70	0.04	0.05	0.07	0.11	0.50
0.75	0.04	0.04	0.06	0.11	0.49
0.80	0.03	0.04	0.06	0.10	0.50
0.85	0.03	0.04	0.06	0.10	0.51
0.90	0.03	0.04	0.06	0.10	0.48
0.95	0.03	0.04	0.06	0.01	0.49
1.00	0.03	0.04	0.05	0.01	0.50

Table 4. Mean relative effort (# of passes) required for local removal of 25 Asian carps in relation to the probability of capture and multiple aggregation rates (i.e., 0.00, 0.25, 0.50, 0.75, and 1.00).

Probability of Capture	**Aggregation = 0.00**	**Aggregation = 0.25**	**Aggregation = 0.50**	**Aggregation = 0.75**	**Aggregation = 1.00**
0.05	69.47	69.88	69.55	70.16	70.60
0.10	33.97	33.98	34.39	34.34	34.32
0.15	22.01	21.95	22.16	22.08	22.23
0.20	16.20	16.21	16.14	16.15	16.09
0.25	12.53	12.45	12.70	12.61	12.54
0.30	10.16	10.25	10.19	10.02	10.14
0.35	8.46	8.35	8.46	8.40	8.31
0.40	7.06	7.13	7.16	7.12	7.09
0.45	6.05	6.04	5.99	6.03	5.97
0.50	5.20	5.24	5.22	5.23	5.25
0.55	4.61	4.62	4.58	4.53	4.54
0.60	3.94	3.93	3.95	3.97	3.93
0.65	3.54	3.52	3.58	3.56	3.43
0.70	2.99	2.99	2.99	2.99	2.96
0.75	2.75	2.76	2.75	2.71	2.62
0.80	2.40	2.39	2.38	2.38	2.33
0.85	1.97	1.96	1.96	1.95	1.86
0.90	1.80	1.79	1.79	1.77	1.60
0.95	1.46	1.48	1.47	1.44	1.31
1.00	0.97	0.96	0.95	0.90	0.50

Table 5. Mean relative effort (# of passes) required for detection in relation to the probability of capture and three response area sizes (75.00 ha, 37.50 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish and an aggregation rate of 0.50.

Probability of Capture	**Area = 75.00 ha (Base Model)**	**Area = 37.50 ha**	**Area = 18.75 ha**
0.05	0.56	0.59	0.55
0.10	0.30	0.30	0.31
0.15	0.20	0.21	0.19
0.20	0.16	0.16	0.16
0.25	0.13	0.13	0.13
0.30	0.11	0.12	0.11
0.35	0.11	0.10	0.10
0.40	0.09	0.01	0.09
0.45	0.08	0.09	0.09
0.50	0.08	0.08	0.08
0.55	0.07	0.08	0.08
0.60	0.07	0.08	0.07
0.65	0.07	0.07	0.07
0.70	0.07	0.07	0.06
0.75	0.06	0.07	0.06
0.80	0.06	0.07	0.06
0.85	0.06	0.06	0.06
0.90	0.06	0.06	0.06
0.95	0.06	0.06	0.06
1.00	0.05	0.06	0.05

Table 6. Mean absolute effort (# of sites) required for detection in relation to the probability of capture and three response area sizes (75.00 ha, 37.50 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish and an aggregation rate of 0.50.

Probability of Capture	**Area = 75 ha (Base Model)**	**Area = 37.50 ha**	**Area = 18.75 ha**
0.05	16,809	8,758	4,275
0.10	8,920	4,514	2,368
0.15	6,067	3,114	1,506
0.20	4,631	2,402	1,242
0.25	3,938	2,006	1,040
0.30	3,386	1,823	856
0.35	3,163	1,550	762
0.40	2,707	1,476	711
0.45	2,467	1,362	671
0.50	2,360	1,184	602
0.55	2,135	1,156	598
0.60	2,141	1,144	560
0.65	1,950	1,031	524
0.70	1,935	999	491
0.75	1,820	981	483
0.80	1,815	973	450
0.85	1,772	963	439
0.90	1,669	903	424
0.95	1,691	831	431
1.00	1,544	820	412

Table 7. Mean relative effort (# of passes) required for local removal in relation to the probability of capture and three response area sizes (75.00 ha, 37.50 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish with an aggregation rate of 0.50.

Probability of Capture	**Area = 75 ha (Base Model)**	**Area = 37.50 ha**	**Area = 18.75 ha**
0.05	69.55	71.17	70.09
0.10	34.39	34.55	34.32
0.15	22.16	22.43	22.24
0.20	16.14	16.56	16.21
0.25	12.70	12.76	12.63
0.30	10.19	10.31	10.05
0.35	8.46	8.55	8.38
0.40	7.16	7.19	7.07
0.45	5.99	6.15	6.07
0.50	5.22	5.36	5.29
0.55	4.58	4.67	4.62
0.60	3.95	4.03	3.93
0.65	3.58	3.65	3.55
0.70	2.99	3.05	2.99
0.75	2.75	2.78	2.76
0.80	2.38	2.44	2.40
0.85	1.96	2.00	1.96
0.90	1.79	1.84	1.79
0.95	1.47	1.49	1.45
1.00	0.95	0.97	0.95

Table 8. Mean absolute effort (# of sites) required for local removal in relation to the probability of capture and three response area sizes (75.00 ha, 37.50 ha, and 18.75 ha). Simulations were based on an abundance of 25 fish with an aggregation rate of 0.50.

Probability of Capture	**Area = 75 ha (Base Model)**	**Area = 37.50 ha**	**Area = 18.75 ha**
0.05	2,081,405	1,064,955	542,786
0.10	1,029,328	516,942	265,794
0.15	663,359	335,582	172,243
0.20	483,041	247,834	125,548
0.25	380,122	191,010	97,775
0.30	304,844	154,270	77,817
0.35	253,223	127,931	64,878
0.40	214,389	107,596	54,739
0.45	179,359	91,953	46,981
0.50	156,094	80,234	40,957
0.55	137,201	69,903	35,738
0.60	118,086	60,328	30,395
0.65	107,025	54,620	27,522
0.70	89,481	45,639	23,141
0.75	82,258	41,640	21,342
0.80	71,342	36,444	18,597
0.85	58,671	29,901	15,149
0.90	53,488	27,468	13,824
0.95	43,904	22,312	11,255
1.00	28,272	14,488	7,336

Table 9. 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) given an abundance of 25 fish. Also shown is the effect of random and systematic sampling.

Probability of Capture	**Aggregation = 0.00 (Systematic)**	**Aggregation = 0.00 (Random)**	**Aggregation = 0.25 (Systematic)**	**Aggregation = 0.25 (Random)**	**Aggregation = 0.50 (Systematic)**	**Aggregation = 0.50 (Random)**	**Aggregation = 0.75 (Systematic)**	**Aggregation = 0.75 (Random)**	**Aggregation = 1.00 (Systematic)**	**Aggregation = 1.00 (Random)**
0.05	16,286	16,404	17,002	16,825	16,809	16,626	17,002	18,819	20,486	29,223
0.10	7,839	8,495	8,100	8,731	8,920	9,079	9,485	10,679	15,931	22,591
0.15	5,551	5,524	5,636	5,815	6,067	6,469	7,153	7,512	15,214	21,042
0.20	4,044	4,090	4,416	4,467	4,631	5,045	6,003	6,155	14,857	21,239
0.25	3,279	3,257	3,563	3,592	3,938	4,112	5,115	5,582	14,929	20,661
0.30	2,662	2,815	2,989	2,978	3,386	3,591	4,661	4,845	14,904	21,035
0.35	2,351	2,412	2,565	2,560	3,163	3,145	4,289	4,631	14,398	21,801
0.40	2,143	1,977	2,281	2,277	2,707	2,806	3,887	4,278	14,893	21,085
0.45	1,860	1,807	2,012	2,186	2,467	2,590	3,790	4,180	15,373	21,437
0.50	1,687	1,649	1,893	1,960	2,360	2,441	3,662	3,933	15,005	20,835
0.55	1,527	1,501	1,739	1,780	2,135	2,199	3,492	3,821	14,571	21,237
0.60	1,395	1,382	1,634	1,671	2,141	2,128	3,279	3,632	14,801	20,906
0.65	1,281	1,282	1,472	1,545	1,950	2,088	3,308	3,448	14,702	21,315
0.70	1,168	1,178	1,378	1,430	1,935	2,020	3,197	3,324	14,821	20,704
0.75	1,112	1,111	1,327	1,357	1,820	1,962	3,198	3,309	14,627	20,912
0.80	1,008	1,043	1,282	1,254	1,815	1,803	3,106	3,261	15,071	20,673
0.85	968	980	1,185	1,212	1,772	1,805	3,021	3,186	15,186	20,925
0.90	901	938	1,118	1,178	1,669	1,732	2,995	3,212	14,468	20,405
0.95	886	897	1,139	1,161	1,691	1,664	2,976	3,136	14,725	20,241
1.00	822	827	1,080	1,071	1,544	1,668	2,904	3,048	14,982	21,031

Table 10. 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) given an abundance of 25 fish. Also shown is the effect of random and systematic sampling.

Probability of Capture	**Aggregation = 0.00 (Systematic)**	**Aggregation = 0.00 (Random)**	**Aggregation = 0.25 (Systematic)**	**Aggregation = 0.25 (Random)**	**Aggregation = 0.50 (Systematic)**	**Aggregation = 0.50 (Random)**	**Aggregation = 0.75 (Systematic)**	**Aggregation = 0.75 (Random)**	**Aggregation = 1.00 (Systematic)**	**Aggregation = 1.00 (Random)**
0.05	2,079,229	2,145,335	2,091,364	2,154,046	2,081,405	2,172,694	2,099,787	2,150,351	2,112,847	2,109,890
0.10	1,016,697	1,078,540	1,017,095	1,080,680	1,029,328	1,076,882	1,027,609	1,071,389	1,027,163	1,036,524
0.15	658,615	717,412	656,969	717,142	663,359	716,484	660,852	708,216	665,312	676,319
0.20	484,876	539,380	485,209	536,351	483,041	537,792	483,481	527,469	481,660	493,111
0.25	374,945	426,254	372,562	427,152	380,122	428,422	377,536	420,230	375,312	383,767
0.30	304,097	361,344	306,720	358,105	304,844	350,142	299,990	344,362	303,542	313,435
0.35	253,078	306,875	249,747	307,065	253,223	300,952	251,503	295,662	248,607	262,006
0.40	211,374	272,348	213,319	269,282	214,389	264,850	213,193	255,898	212,114	220,005
0.45	181,090	240,610	180,682	238,296	179,359	230,574	180,459	226,948	178,661	190,958
0.50	155,747	217,488	156,829	210,318	156,094	211,234	156,494	201,039	157,037	166,271
0.55	138,075	196,141	138,146	192,910	137,201	187,828	135,689	178,120	135,736	142,715
0.60	117,862	179,628	117,675	176,096	118,086	172,631	118,924	162,664	117,699	125,793
0.65	105,790	165,432	105,412	164,217	107,025	156,855	106,427	147,297	102,760	110,673
0.70	89,516	153,322	89,409	149,483	89,481	143,969	89,433	135,359	88,520	96,181
0.75	82,291	142,492	82,559	139,252	82,258	133,158	81,136	123,038	78,291	85,042
0.80	71,901	132,404	71,438	130,102	71,342	123,017	71,123	113,893	69,851	75,571
0.85	58,864	126,603	58,678	119,939	58,671	115,172	58,262	102,067	55,791	63,501
0.90	53,867	121,004	53,664	113,301	53,488	106,316	52,944	91,389	47,840	54,013
0.95	43,703	112,389	44,140	105,572	43,904	97,168	43,167	81,611	39,177	41,896
1.00	29,089	108,236	28,823	100,091	28,272	87,900	27,067	70,110	14,982	21,031

Table 11. 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 (37.50 ha and 18.75 ha), and whether the sampling buffer was large or small. Results are shown against the base model results.

Probability of Capture	**75.00 ha (Base Model)**	**37.50 ha (Large Buffer)**	**37.50 ha (Small Buffer)**	**18.75 ha (Large Buffer)**	**18.75 ha (Small Buffer)**
0.05	16,809	18,938	8,758	19,977	4,275
0.10	8,920	9,964	4,514	13,463	2,368
0.15	6,067	7,213	3,114	9,550	1,506
0.20	4,631	5,529	2,402	7,745	1,242
0.25	3,938	4,551	2,006	6,773	1,040
0.30	3,386	3,861	1,823	5,737	856
0.35	3,163	3,497	1,550	5,495	762
0.40	2,707	3,210	1,476	4,825	711
0.45	2,467	2,945	1,362	4,585	671
0.50	2,360	2,676	1,184	4,479	602
0.55	2,135	2,452	1,156	4,421	598
0.60	2,141	2,306	1,144	4,059	560
0.65	1,950	2,233	1,031	3,938	524
0.70	1,935	2,035	999	3,820	491
0.75	1,820	2,041	981	3,794	483
0.80	1,815	1,945	973	3,679	450
0.85	1,772	1,913	963	3,519	439
0.90	1,669	1,787	903	3,440	424
0.95	1,691	1,676	831	3,560	431
1.00	1,544	1,707	820	3,353	412

Table 12. 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 (37.50 ha and 18.75 ha), and whether the sampling buffer was large or small. These results are compared to the base model results.

Probability of Capture	**75.00 ha (Base Model)**	**37.50 ha (Large Buffer)**	**37.50 ha (Small Buffer)**	**18.75 ha (Large Buffer)**	**18.75 ha (Small Buffer)**
0.05	2,081,405	2,092,518	1,064,955	2,095,421	542,786
0.10	1,029,328	1,017,861	516,942	1,016,369	265,794
0.15	663,359	661,412	335,582	669,437	172,243
0.20	483,041	487,050	247,834	478,052	125,548
0.25	380,122	374,222	191,010	378,346	97,775
0.30	304,844	301,889	154,270	305,731	77,817
0.35	253,223	254,719	127,931	256,569	64,878
0.40	214,389	210,976	107,596	212,087	54,739
0.45	179,359	179,182	91,953	179,237	46,981
0.50	156,094	157,929	80,234	160,236	40,957
0.55	137,201	138,516	69,903	140,358	35,738
0.60	118,086	118,717	60,328	118,630	30,395
0.65	107,025	109,512	54,620	108,884	27,522
0.70	89,481	89,738	45,639	89,258	23,141
0.75	82,258	83,039	41,640	83,375	21,342
0.80	71,342	73,955	36,444	75,536	18,597
0.85	58,671	58,872	29,901	58,596	15,149
0.90	53,488	54,331	27,468	54,271	13,824
0.95	43,904	46,448	22,312	47,423	11,255
1.00	28,272	28,477	14,488	27,408	7,336

Table 13. 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 1.0.

Probability of Capture	**Sample = 1 (Base Model)**	**Sample = 3**	**Sample = 4**	**Sample = 5**
0.05	70.60	49.48	42.95	39.37
0.10	34.32	20.03	17.05	14.86
0.15	22.23	11.35	9.58	7.82
0.20	16.09	7.80	6.14	5.11
0.25	12.54	5.56	4.38	3.57
0.30	10.14	4.25	3.31	2.52
0.35	8.31	3.39	2.58	1.99
0.40	7.09	2.80	1.95	1.75
0.45	5.97	2.23	1.79	1.55
0.50	5.25	1.86	1.61	1.14
0.55	4.54	1.69	1.32	0.78
0.60	3.93	1.55	0.96	0.64
0.65	3.43	1.33	0.73	0.57
0.70	2.96	1.00	0.60	0.53
0.75	2.62	0.73	0.55	0.51
0.80	2.33	0.62	0.52	0.50
0.85	1.86	0.55	0.49	0.51
0.90	1.60	0.51	0.50	0.50
0.95	1.31	0.50	0.50	0.50
1.00	0.50	0.49	0.50	0.50

Table 14. 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.

Probability of Capture	**Aggregation = 0.75 Sample = 1 (Base Model)**	**Aggregation = 0.75 Sample = 3**	**Aggregation = 0.75 Sample = 4**	**Aggregation = 0.75 Sample = 5**	**Aggregation = 1.00 Sample = 1 (Base Model)**	**Aggregation = 1.00 Sample = 3**	**Aggregation = 1.00 Sample = 4**	**Aggregation = 1.00 Sample = 5**
0.05	70.16	63.62	61.04	59.26	70.60	49.48	42.95	39.37
0.10	34.34	28.87	27.15	25.90	34.32	20.03	17.05	14.86
0.15	22.08	17.73	16.38	15.45	22.23	11.35	9.58	7.82
0.20	16.15	12.34	11.33	10.68	16.09	7.80	6.14	5.11
0.25	12.61	9.13	8.41	7.76	12.54	5.56	4.38	3.57
0.30	10.02	7.26	6.51	5.89	10.14	4.25	3.31	2.52
0.35	8.40	5.70	5.01	4.60	8.31	3.39	2.58	1.99
0.40	7.12	4.68	4.09	3.72	7.09	2.80	1.95	1.75
0.45	6.03	3.81	3.40	2.95	5.97	2.23	1.79	1.55
0.50	5.23	3.21	2.80	2.47	5.25	1.86	1.61	1.14
0.55	4.53	2.75	2.26	1.94	4.54	1.69	1.32	0.78
0.60	3.97	2.29	1.88	1.71	3.93	1.55	0.96	0.64
0.65	3.56	1.88	1.62	1.39	3.43	1.33	0.73	0.57
0.70	2.99	1.65	1.32	1.13	2.96	1.00	0.60	0.53
0.75	2.71	1.32	0.99	0.98	2.62	0.73	0.55	0.51
0.80	2.38	0.99	0.96	0.96	2.33	0.62	0.52	0.50
0.85	1.95	0.96	0.95	0.94	1.86	0.55	0.49	0.51
0.90	1.77	0.93	0.93	0.93	1.60	0.51	0.50	0.50
0.95	1.44	0.91	0.91	0.92	1.31	0.50	0.50	0.50
1.00	0.90	0.90	0.90	0.90	0.50	0.49	0.50	0.50

Table 15. 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.

Probability of Capture	**Abundance = 20 Sample = 1 (Base Model)**	**Abundance = 20 Sample = 3**	**Abundance = 20 Sample = 4**	**Abundance = 20 Sample = 5**	**Abundance = 25 Sample = 1 (Base Model)**	**Abundance = 25 Sample = 3**	**Abundance = 25 Sample = 4**	**Abundance = 25 Sample = 5**
0.05	66.08	47.45	42.67	38.12	70.60	49.48	42.95	39.37
0.10	32.03	19.36	16.53	14.31	34.32	20.03	17.05	14.86
0.15	20.60	11.37	9.02	7.60	22.23	11.35	9.58	7.82
0.20	15.05	7.54	5.90	4.87	16.09	7.80	6.14	5.11
0.25	11.71	5.43	4.19	3.45	12.54	5.56	4.38	3.57
0.30	9.51	3.97	3.03	2.45	10.14	4.25	3.31	2.52
0.35	7.81	3.23	2.40	1.94	8.31	3.39	2.58	1.99
0.40	6.62	2.63	1.91	1.71	7.09	2.80	1.95	1.75
0.45	5.69	2.08	1.72	1.40	5.97	2.23	1.79	1.55
0.50	4.83	1.77	1.53	0.94	5.25	1.86	1.61	1.14
0.55	4.28	1.63	1.18	0.72	4.54	1.69	1.32	0.78
0.60	3.72	1.48	0.83	0.62	3.93	1.55	0.96	0.64
0.65	3.23	1.22	0.68	0.54	3.43	1.33	0.73	0.57
0.70	2.81	0.86	0.59	0.52	2.96	1.00	0.60	0.53
0.75	2.48	0.68	0.54	0.50	2.62	0.73	0.55	0.51
0.80	2.12	0.59	0.52	0.50	2.33	0.62	0.52	0.50
0.85	1.75	0.54	0.51	0.49	1.86	0.55	0.49	0.51
0.90	1.55	0.50	0.50	0.49	1.60	0.51	0.50	0.50
0.95	1.23	0.50	0.48	0.49	1.31	0.50	0.50	0.50
1.00	0.50	0.49	0.50	0.50	0.50	0.49	0.50	0.50

Table 16. 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.

Probability of Capture	**Avoidance = 0.00**	**Avoidance = 0.05**	**Avoidance = 0.25**	**Avoidance = 0.50**	**Avoidance = 0.75**
0.05	0.56	0.59	0.67	0.90	1.53
0.10	0.30	0.30	0.36	0.51	0.84
0.15	0.20	0.21	0.26	0.37	0.62
0.20	0.16	0.17	0.20	0.29	0.52
0.25	0.13	0.14	0.17	0.25	0.45
0.30	0.11	0.12	0.15	0.22	0.39
0.35	0.11	0.11	0.13	0.20	0.36
0.40	0.09	0.10	0.12	0.18	0.32
0.45	0.08	0.09	0.11	0.16	0.31
0.50	0.08	0.08	0.10	0.15	0.29
0.55	0.07	0.08	0.10	0.14	0.28
0.60	0.07	0.08	0.09	0.14	0.27
0.65	0.07	0.07	0.09	0.13	0.24
0.70	0.07	0.07	0.09	0.12	0.23
0.75	0.06	0.07	0.08	0.12	0.23
0.80	0.06	0.06	0.08	0.11	0.22
0.85	0.06	0.06	0.08	0.11	0.21
0.90	0.06	0.06	0.07	0.10	0.21
0.95	0.06	0.06	0.07	0.10	0.20
1.00	0.05	0.06	0.07	0.11	0.20

Table 17. 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.

Probability of Capture	**Avoidance = 0.00**	**Avoidance = 0.05**	**Avoidance = 0.25**	**Avoidance = 0.50**	**Avoidance = 0.75**
0.05	69.55	72.02	81.80	106.02	178.82
0.10	34.39	34.77	40.40	51.52	87.65
0.15	22.16	22.85	25.95	33.86	57.97
0.20	16.14	16.71	19.13	25.20	42.67
0.25	12.70	12.77	14.83	19.49	33.74
0.30	10.19	10.44	12.00	16.01	27.89
0.35	8.46	8.58	10.04	13.27	23.29
0.40	7.16	7.27	8.49	11.44	20.23
0.45	5.99	6.24	7.35	9.93	17.69
0.50	5.22	5.47	6.41	8.62	15.50
0.55	4.58	4.78	5.51	7.64	13.87
0.60	3.95	4.09	4.90	6.85	12.41
0.65	3.58	3.66	4.39	6.10	11.31
0.70	2.99	3.20	3.86	5.42	10.30
0.75	2.75	2.83	3.40	4.86	9.27
0.80	2.38	2.50	2.99	4.33	8.45
0.85	1.96	2.00	2.65	3.95	7.78
0.90	1.79	1.85	2.32	3.43	7.00
0.95	1.47	1.56	1.95	3.02	6.28
1.00	0.95	0.98	1.55	2.53	5.62