Fishery Bulletin

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Journal:	*Fishery Bulletin*
Manuscript ID	FB-2021-0016-A.R1
Manuscript Type:	Full Article- Fishery Bulletin
Keywords:	Fisheries, Gear Efficiency, Hydraulic Dredge, Bivalves, Depletion Experiments

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Discriminating between high- and low-quality field depletion experiments using forensic evidence

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Competing interests: The authors declare there are no competing interests.

Abstract

Between 1997 and 2011, the National Marine Fisheries Service conducted 50 depletion experiments to estimate survey gear efficiency and stock density for Atlantic surfclam (*Spisula* *solidissima*) and ocean quahog (*Arctica islandica*) populations using commercial hydraulic dredges. The Patch Model was formulated to estimate gear efficiency and organism density from the depletion experiment data. The range of efficiencies estimated is substantial, leading to uncertainty in the application of these estimates in stock assessment. Known values of four measures of experimental performance for each of the 50 in-field depletion experiments were compared to those same metrics from 9,000 simulated depletion experiments, assumed to represent a suite of conditions that might also occur in the corresponding field experiment. These comparisons allow for analyses of the quality of field experiments that would otherwise not be possible and provide an evidentiary basis for weighting the results of field experiments beyond traditional measures of uncertainty. The performance metrics were used to implicate a subset of in-field experiments that are more likely to have produced inaccurate gear efficiency estimates, potentially biasing the efficiency estimates low for the entire depletion dataset.

Introduction

The implementation of a definitive measure of dredge efficiency for shellfish survey data substantially improves the estimation of abundance. Commonly, depletion experiments are used to estimate gear efficiency and population density in a target area for sessile and sedentary species (Leslie & Davis, 1939; Skalski et al., 1983; Lasta & Iribarne, 1997; Gedamke et al., 2005; Wilberg et al., 2013), although other quantification methods have also been used (Chai et al., 1992; Ragnarsson & Thórarinsdóttir, 2002; Morson et al., 2018). Efficiency estimates exist for a range of dry dredges that are designed to harvest epibenthic animals, including oyster dredges (Morson et al., 2018; Powell et al. 2,007), clam dredges (Pezzuto et al., 2010), crab dredges (Vølstad et al., 2000; Wilberg et al., 2013), and scallop dredges (Beukers-stewart & Beukers-stewart, 2009; Lasta & Iribarne, 1997). By comparison, highly efficient hydraulic dredges are the primary gear type used to harvest infaunal clams (Da Ros et al., 2003; Hauton et al., 2003; Moschino et al., 2003; Gilkinson et al., 2005; Meseck et al., 2014). Hydraulic dredges increase the catchability of the target organism by using water pressure to liquefy the sediment (Da Ros et al., 2003; Gilkinson et al., 2003; Hauton et al., 2007; Meseck et al., 2014).

The ocean quahog and the Atlantic surfclam support substantial fisheries on the northeast U.S. continental shelf and are harvested exclusively by hydraulic dredges due to the depths at which they are found. A typical hydraulic dredge is a large rectangular box between 2.4 and 4.0-m wide, constructed of evenly spaced steel bars that is towed over a seabed (Lambert & Goudreau, 1996; Meyer et al., 1981). A manifold at the head of the dredge distributes high-pressure water provided by a shipboard water pump through a connecting hose. The water is focused through a series of jets onto the seabed, liquefying the sediment and unearthing the clams for easy capture by the dredge. Hydraulic dredges, widely used in clam fisheries (Parker, 1971; Hauton et al., 2007; Sala et al., 2017), are necessary for the commercial harvest of ocean quahogs and surfclams due to the depth and distance from the shore at which these species are found and the fact that the fishery is based on a high volume, low unit cost product. Thus, rapid and efficient capture methods are economically essential.

A series of depletion experiments was conducted between 1997 and 2011 on commercial clam vessels targeting Atlantic surfclam (*Spisula solidissima*) and ocean quahog (*Arctica islandica*) populations to estimate the efficiency of both commercial hydraulic dredges. The locations of these depletion experiments are specified in Appendix 3 of NEFSC (2017a) (Fig. 1-2). As is often the case in measures of dredge efficiency, individual experiments varied widely in their estimates of efficiency (Vølstad et al., 2000; Powell et al., 2007; Hennen et al., 2012; Wilberg et al., 2013; Morson et al., 2018). Very little is known about how environmental and sampling variables influence the efficiency of a hydraulic dredge, factors that are likely the source of between-experiment variation. Estimates of gear efficiency based on depletion experiments are a key source of uncertainty in the stock assessments for the Atlantic surfclam and ocean quahog stocks as a consequence.

The Patch Model was developed to analyze the results of depletion experiments to estimate the efficiency of capture of sedentary species such as surfclams and ocean quahogs (Rago et al., 2006). The Patch Model has been rigorously tested by previous studies (Hennen et al., 2012) and has been used to inform stock assessments of commercially fished species in the mid-Atlantic, such as Atlantic surfclam, ocean quahog, monkfish (Lophius americanus: NEFSC, 2010a) and Atlantic sea scallop (Placopecten magellanicus: NEFSC, 2010b; NMFS, 2009). Over the span of 14 years, 50 depletion experiments were carried out along the U.S. Mid-Atlantic continental shelf off the coast of Massachusetts, Long Island, New Jersey, and the Delmarva Peninsula to determine the efficiency of hydraulic dredges used in the surfclam and ocean quahog fisheries. The Patch Model provides estimates of capture efficiency and average density of organisms in the target area by tracking the relative reduction in catch for each dredge tow. Theoretically, capture efficiency is a measurable characteristic of the gear as well as the species (Hennen et al., 2012).

A field depletion experiment is designed to have the dredge towed over the same ground repeatedly while covering the majority of a predetermined area; typically, in the experiments considered herein, a long rectangular area, the smallest rectangular area that contains all the tows, on average about 10 dredge widths wide (23-24-m) and about 400-1000-m long. A series of intersecting dredge tows are conducted across the selected area, with the dredge tow path beginning at one short end of the rectangle and finishing at the opposite end (Fig. 3). The dredge paths are not parallel, rather the paths overlap and intersect at various points in the area by design in order to meet the requirements of the Patch Model. See Figure 3 for a visual representation of dredge tows in an experiment area. The experiment requires the assumption that all catches are random samples and that no transport of organisms into or out of the study site occurs during the experiment (Leslie & Davis, 1939). The catch and the incremental dredge positions are recorded for each dredge tow. Over the course of the depletion experiment, the catch per tow will decrease; this rate of decline is proportional to the efficiency of the dredge (Hennen et al., 2012). If the rate of decline is steep, the dredge is highly efficient, and if it is shallow, the dredge may not be efficient.

Field depletion experiments can take hours to complete and require much effort on the part of scientists and crew on the ship. Therefore, it is important to know if the experiments that have been conducted produced reliable efficiency estimates for the gear used and to evaluate characteristics leading to poor performance that might be avoided in future endeavors. Poussard et al. (2021) uses simulation analysis to determine best practices for depletion experiments and evaluates which range of experiment protocols were most likely to provide high quality capture efficiency estimates. This manuscript aims to use the simulation data to identify in-field depletion experiments that were of high quality, and those that were of lower quality. The National Marine Fisheries Service (NMFS) depletion dataset analyzed is unique; at the time of this writing, no other depletion dataset is this expansive.

Analyzing the NMFS hydraulic dredge depletion experiments may provide an improved understanding of the sources of uncertainty in efficiency estimates derived in this way, including the characteristics of experimental protocol and environmental factors affecting gear efficiency. This study first summarizes the characteristics of these experiments (e.g., dredge size, depth, and geographic region) and then compares simulated depletion experiments to the field depletion experiments conducted on Atlantic surfclam and ocean quahog stock using a series of experimental quality metrics. The simulated depletion experiments have the advantage of being fully controlled and they can be evaluated for the accuracy and precision of the parameter estimates they provide. In this analysis, a set of simulated experiments is matched to each field experiment. This set of simulated experiments is assumed to represent a suite of conditions that might also occur in the corresponding field experiment. These comparisons allow for analyses of the quality of field experiments and provide an evidentiary basis for weighting the results of field experiments beyond traditional measures of uncertainty.

Methods

The Patch Model

To estimate the catchability coefficient, depletion experiments permit correction of survey catch using the equations $N = SA/q$ and $q = \frac{\alpha e}{A}$, where N is stock abundance or biomass and SA is the swept area average of all tows in the experiment area. The catchability coefficient q is obtained from α, the area swept by the sampling gear, e, the dredge efficiency, and A, the spatial domain of the estimates (Paloheimo & Dickie 1964). The area swept by the dredge is calculated as the distance the dredge is towed multiplied by the width of the dredge. See Figure 3 for a visual of the dredge tows in an experiment area.

The expected catch of organisms in any tow i, $E(C_i)$, given initial density of the target organisms (D_0) and the cumulative catch from previous tows, T_{i-1}, can be calculated as:

(1) $$E(C_i) = q(D_0 - T_{i-1})$$

assuming each tow covers the same spatial domain. In reality, this relationship is more complex as each tow covers only a portion of the experimental area. Incorporating the portion of the area that has already been hit by the dredge prior to tow i, also known as the hit matrix (Hennen et al.

2012), gives the expected catch per tow *i* as:

(2) $$E(C_i) = (EAS_i)D_o$$

where D_0 is the initial density of the target organism in the area and EAS is the effective area swept defined as the total area swept (ft^2) by the dredge in tow *i* taking into account the portion of the experimental area hit by the dredge in previous tows. EAS is calculated as:

(3) $$EAS = ea_i\sum_{j=1}^{i} f_{i,j}(1 - e\gamma)^{j-1}$$

where *e* is the capture efficiency as estimated by the Patch Model, a_i is the area swept by tow *i*, $f_{i,j}$ is the fraction of the area a_i that was hit by the dredge *j* times in previous tows, and γ is the ratio of the cell size and the dredge width. Rago et al. (2006) divided the experimental area into cells twice the width of the dredge. Hennen et al. (2012) removed γ by reducing the cells to points, eliminating the need to calculate cell size, which results in improved accuracy and precision of efficiency estimates. This study uses the latter method.

The negative binomial distribution is used to describe the dispersion of animals in the experiment area in order to account for extra variation in observed catches and take into account catch from previous tows when estimating catch in tow *i*.. This method uses the cumulative spatial pattern of animal removals to define capture probability for each organism. The negative binomial distribution of catch can be expressed as a function of D_o (initial density of organisms), *k* (the dispersion parameter), and EAS (the effective area swept in tow *i*) (Rago et al., 2006): thus,

(4) $$Pr(Ci|D_0, k,\ EAS) = \left(\frac{k}{D_0(EAS)+K}\right)^k \left(\frac{D_0(EAS)}{D_0(EAS)+k}\right)^{C_i} x\prod_{j=1}^{C_i}\frac{k+j-1}{j}\quad .$$

The log likelihood function allows estimation of the dispersion parameter, initial density, and capture efficiency, given the hit matrix, catch and area swept.

$$(5)\ \mathrm{LL}(D_0, k, e, \gamma \mid Ci, EAS) = k\textstyle\sum_{i=1}^{I}\log(k) - \log(D_0(EAS) + k)) +$$

$$\textstyle\sum_{i=1}^{I}(log\ (D_0(EAS)) - log\ (D_0(EAS) + k)) + \sum_{i=1}^{I}\sum_{j=1}^{Ci} log\ (k + j - 1) - \sum_{i=1}^{I} Ci!.$$

Simulated Datasets

Poussard et al. (2021) report the results of 5,400 simulated depletion experiments conducted in a block design in which animal density, true dredge efficiency, the number of tows per experiment, and the dispersion of animals on the bottom were varied. For the purposes of this study, 3,600 additional simulations with 15 and 25 dredge tows were conducted in order to provide a simulated dataset that is comparable to the in-field experiments, for a total of 9,000 simulations (Table 1). The simulated dataset included 5 options for the number of dredge tows for each experiment, 4 dispersions of clams in the area, 3 clam densities, and 3 values for the 'true' efficiency of the dredge. Fifty simulations were conducted for each combination of factors (e.g., fifty simulations were conducted with 25 tows with a dredge efficiency of 0.9 and clams distributed evenly through the area with a density of 3 clams m^{-2}, and 50 more were conducted with all the same factors except with a density of 1.5 clams m^{-2} and so on). Fifty tow patterns were randomly generated for each tow number. Here we discuss four useful metrics for comparing depletion experiments, along with the estimates of efficiency and density. The four metrics are the average effective area swept (EAS) (Equation 3), the coefficient of variation (CV) for the efficiency estimate (cv_e), the CV of the *k* parameter (cv_K) (the negative binomial dispersion parameter), and the overlap score describing tow overlap (Equation 7). The CVs were calculated using the delta method standard deviation of the Patch Model estimates divided by the means of the estimates obtained from the log likelihood equation (Equation 5).

The overlap score (OS) is a metric describing tow overlap that does not depend on estimated efficiency, or the spatial dimensions of the site. OS is derived directly from the hit matrix

(Hennen et al., 2012) where the *n* rows equal the number of tows in the experiment and the *m* columns are the number of points touched *m* times previously. The highest possible amount of overlap for any depletion site would be the exact duplication of the longest tow in each sequence (the row with the most total points touched), repeated *n* times (OS_{max}). For tow *i*:

$$OS_i = \sum_{h=i}^{m} (p_{i,h} h) \quad (6)$$

where $p_{i,h}$ are the number of points in the hit matrix row *i* and column *h*. The OS for each tow sequence is then

$$OS = \frac{\sum_i^n OS_i}{OS_{max}} \times 100 \quad (7)$$

where *n* is the total number of tows in the sequence. The value of *OS* varied nonlinearly with tow number. As a consequence, the values were detrended by using the mean *OS* value for that tow number to standardize all OS values of the same tow number. A higher value of *OS* equates to more dredge overlap in the tow structure of an experiment for a given number of tows.

For the simulations, where the true efficiency was already known, Poussard et al. (2021) calculated the percent error in efficiency from the Patch Model estimate of efficiency, *EstEff*, and the inherent efficiency specified in the simulation, *TrueEff*, as:

$$Error = \frac{EstEff - TrueEff}{TrueEff} \times 100. \quad (8)$$

Analysis of simulated depletion experiments by Poussard et al. (2021) concluded that a depletion experiment is more likely to produce accurate gear efficiency estimates if it employs a higher number of dredge tows, maximizes the amount of intersection in tow paths, occurs over a homogenous as opposed to patchy distribution of clams, and a highly efficient dredge. The results of these simulations were compared to the field depletion experiments using the set of 4 metrics to match the field experiments to simulated experiments with similar characteristics. The known errors in the set of comparable simulated experiments were then used as a proxy for the reliability of each of the 50 field experiments.

Application of Simulations: Error Estimates

Field experiments varied in the length of the depletion site and the width of the dredge used. For statistical analysis, EAS was standardized to a dredge width of 3.81-m and a site length of 960-m consistent with the simulation dataset of Poussard et al. (2021), using a proportional standardization. All EAS values used were the average values per tow, rather than the total values, to take into account the large range in tow numbers among experiments.

A Principal Components Analysis was conducted on the simulation dataset to determine if the 4 metrics describing depletion performance (EAS, cv_E, cv_K, and OS) were correlated and, if so, to derive new orthogonal metrics. The data were standardized to a mean of 0 and a standard deviation of 1 and factors were designated using Varimax rotation. Factor loadings showed that each of the four metrics loaded on separate axes with loads exceeding 0.95; thus, the 4 metrics in their original form are approximately orthogonal and provide independent information for evaluating experimental performance.

Field experiments were matched to a subset of the simulated depletion experiments through an iterative process. For each field experiment, the values of the 4 metrics were compared to the 9,000 simulations. Experiments were compared to the simulation dataset by determining whether the values of each of the four metrics for a given in-field depletion experiment fell above or below the mean value for the metric from the simulation dataset. This generated a 4-digit integer sequence (e.g., 1011) for any given field experiment with a 1 assigned if the field experiment metric fell above the mean of the simulated experiments metrics and a 0 if below. The same set of integer sequences were calculated for each simulation and compared to the mean of the metrics for all simulated experiments. Then the subset of simulations having the same sequence as the in-field experiment was extracted from the dataset. The means of the metrics for this subset were again calculated and compared to the field experiment, generating a new 4-digit sequence. This sequence, in turn, was used to extract a subset of simulated experiments of identical sequence. This process was repeated sequentially on each extracted subset, with the mean values for the simulated experiments being updated using only the extracted subset, until none of the final subset of simulations had the same 4-digit value as the chosen field experiment. These were considered to be the most comparable simulations to the field experiment in question. This "most comparable" subset typically numbered 2-20 of the 9,000 simulations and was used to describe the average simulated four metrics and the average error in efficiency most appropriate for comparison to the known (Tables 2 and 3).

Each simulation in the extracted subset of simulations was run using a specified dispersion of clams. The distributions of clams were organized as follows: a relatively uniform distribution across the depletion rectangle (denoted as NP), patches oriented across the narrow dimension (P), patches oriented longitudinally (HP), and patches of a triangular nature emanating from one side of the rectangle (T) (Fig. 3). The fraction of chosen simulations assigned to each in-field experiment falling into each of these categories was obtained to describe possible similarities in clam dispersion characteristics in the area occupied by the in-field depletion experiment.

Comparisons between field experiments and simulations were made using 4 error terms chosen to determine which of the in-field depletion experiments diverged the most from the identified "most comparable" simulations using the 4-integer test. Two error terms describe how closely the 4 experiment metrics derived from the field experiments (EAS, cv_E, cv_k, and OS) agreed with the same metrics obtained from the extracted subset of the simulations, henceforth referred to as Err1 and Err2:

(9) $$Err1 = \sum_{j=1}^{4} \frac{abs(observed - expected)}{expected}$$

(10) $$Err2 = \sum_{j=1}^{4} \frac{(observed - expected)^2}{expected}$$

where the observed metric is obtained from the field experiment and the expected metric is the average value of the extracted simulations.

Err3 is the average percent error obtained from the simulation subset obtained by comparing the field estimate of efficiency with the known efficiency used in the simulation (Equation 8). Err3 was modified as a simple difference between the averages obtained from the simulation subset as Err4:

(11) $$Err4 = abs(obseff\text{-}trueeff)$$

Caveat lector; no metric exists that can definitively estimate the accuracy of an in-field depletion experiment, as the true efficiency perforce is unknown. The four error estimates relate attributes of a large set of simulated experiments, which use combinations of 4 different depletion experiment characteristics to describe how precisely the Patch Model estimate of efficiency returned the known efficiency specified in the simulation. In this study, we use these four error estimates to identify in-field experiments which have characteristics that resemble the 4 performance characteristics in the simulations of Poussard et al. (2021): the cv_E, cv_K, the OS, and the EAS.

Statistics

Unless otherwise indicated, statistics used SAS Version 9. Field experiments that fell at or above the 80th percentile for one or more of the 4 error estimates were compared to the remaining experiments falling below the 80th percentile using a Wilcoxon rank sum test (Sokal & Rohlf,

1998) to determine if the flagged subset of in-field experiments were a random subset of all in-field experiments, as determined by the 4 error estimates and other metrics as earlier described.

The relationship between descriptors of Patch Model performance, including efficiency and density estimates, and descriptors of the experiment such as location, depth, and target species in the field experiments were resolved using correspondence analysis (Clausen, 1998). For this purpose, continuous variables were classified into quartiles (1-4), and error terms were entered as 1 (below the 80th percentile) or 2 (at or above the 80th percentile) (Table 4). Table 4 identifies the variables used to specify the coordinate system for the correspondence analysis and a series of supplementary variables assigned coordinate positions (Clausen, 1998). Of note, the error terms were all designated supplementary variables, meaning that they did not determine the axes in the correspondence analysis and were added retrospectively to provide context.

Pearson correlations (R Core Team, version 3.6.0) were conducted on variables describing the in-field experiments to determine how factors such as dredge width, experiment area width, number of tows, year, and latitude correlated with Patch Model efficiency, density, and *k*-parameter estimates.

Results

Field Depletion Experiment Characteristics

The mean and median efficiency estimates, density estimates, and *k*-parameter estimates for the 50 in-field depletion experiments are provided in Table 5. The mean value of the efficiency estimates for the 31 depletion experiments targeting surfclams is 0.635 and the mean value of the efficiency estimates for the 19 depletion experiments targeting ocean quahogs is 0.586 (Fig. 4). The mean density estimate for surfclam depletion experiments is 1.496 clams m^{-2} and the mean density estimate for ocean quahog depletion experiments is 1.184 clams m^{-2}. These densities are well above the average stock density for both species as the depletion experiments were purposely sited in high-density areas. The mean *k*-parameter estimate for the surfclam experiments is 12.097 and the mean for the ocean quahog experiments is 7.724.

Most depletion experiments targeting ocean quahogs were conducted at higher latitudes and at deeper depths than depletion experiments targeting surfclams (Table 6). For ocean quahog depletion experiments, higher efficiency estimates were produced further north (Fig. 1). Surfclam depletion experiments produced higher efficiency estimates off the coast of New Jersey (Fig. 2).

Over the 14 years that depletion experiments were conducted, methodology and gear changed. Dredge width, for example, gradually increased from 2.55-m to 3.8- m. The number of dredge tows used in each experiment varied through the years as well. The majority of experiments, especially in later years, used between 15 and 20 tows, but some experiments between 1997 and 2000 used as few as 4 dredge tows and as many as 39 tows.

Correlation Analysis

Efficiency estimates for ocean quahog depletion experiments are significantly positively correlated with latitude (see Fig. 1) and the width of the dredge (Fig. 5). Efficiency is incorporated into the equation to calculate EAS, therefore the correlation between efficiency and EAS is expected and correlations between efficiency and other variables will be reflected by correlations between EAS and those same variables. Year is incorporated into the correlation analysis to see how parameters changed over time. As noted, dredge width increases with year, and tow number and depth decrease over time. The cv_E, is negatively correlated with the number of tows and strongly positively correlated with the CV of the density estimate (cv_D) (Fig. 5-6). In surfclam depletion experiments, as opposed to ocean quahog experiments, the cv_K is significantly positively correlated with the cv_D (Fig. 6). In the case of surfclams, no correlation exists between latitude and the efficiency estimates, but density estimates are negatively correlated with the latitude and efficiency estimates.

Error Estimates and Wilcoxon Tests

In-field depletion experiments with parameter estimates that fell at or above the 80^{th} percentile of their respective "most comparable" simulated experiments, for one or more of the four error estimates are denoted by asterisks in Table 6. The 80^{th} percentile, corresponding to a 90^{th} percentile one-sided threshold, was used to retain a high probability of including marginal experiments in the group flagged as suspect, recognizing that this threshold may entrap some experiments of higher quality. Effectively, the result was to err on the side of removing a few "good" field depletion experiments rather than keep a few "bad" ones.

Of the 50 depletion experiments, 24 fell at or above the 80^{th} percentile for one or more of the error estimates. Experiments falling at or above the 80^{th} percentile for error terms Err1 (Equation 9) and Err2 (Equation 10) are experiments that differed substantially from the chosen subset of simulations for one or more of the four metrics describing the depletion experiments, the cv_E, the cv_K, the number of tows, and the EAS. These in-field experiments were not well described by the most similar subset of simulations. The possibility that the range of values for EAS might influence the differential in the results for Err1 and Err2 was tested by recomputing Err2 using $\log_e$(EAS). The set of experiments flagged by Err2 did not change.

Err3 (Equation 8) and Err4 (Equation 11) were used to identify field experiments using an alternate method to infer poorly estimated efficiency. In this case, comparison was made to error estimates from a subset of similar simulations each with a known error estimate. Field experiments most similar to simulation subsets that yielded high Err3 and Err4 were flagged (defined by falling at or above the 80th percentile).

When in-field experiments produced parameter estimates that fell at or above the 80th percentile for an error term (they are then "flagged" by that error term; Table 7), are compared to the experiments below the 80th percentile, some differences in Patch Model estimates of gear efficiency and clam density come to light. These highlight that the four error metrics are operationally different and evaluate experiment performance in different ways. For example, the experiments that were flagged by Err2, Err3, and Err4 have lower average and median efficiency estimates than experiments flagged by Err1. The relationships between the in-field experiments flagged by one or more error terms with the rest of the dataset were evaluated using Wilcoxon rank sums tests (Table 8). Experiments flagged by Err1 did not differ significantly from the remaining experiments for any of the measured depletion parameters. In each case, the identified experiments were distributed randomly within the full set of in-field experiments with respect to the different error terms tested. If the experiments flagged by Err1 are removed from the analysis, the mean and median efficiency estimates of the remaining in-field depletion experiments are not significantly different from the mean and median estimates for the entire dataset. In dramatic contrast, for experiments flagged by Err2, Err3, and Err4, the Patch Model efficiency estimates differed substantially from the remaining in-field experiments. In addition, experiments flagged by Err3 and Err4 had substantially different cv_K and EAS values than experiments that were not flagged (Table 9). Interestingly, all 9 experiments flagged by Err3 were among the 10 flagged by Err4, yet Err3 experiments display significantly different cv_E and cv_D estimates whereas the group of experiments flagged by Err4 do not.

Correspondence Analysis

Correspondence analysis shows that variance in descriptor metrics is primarily explained by the first 2 axes (Fig. 7). Table 4 describes the abbreviations in the Figures 7-9. The experiments flagged by the error terms (R1-4) are included as supplementary variables. The dispersions of clams (Fig. 3) were also added as supplementary variables, however they are not included in the figures because each fell near the center of the correspondence plot. Dimension 1 (Fig. 7-8) is determined primarily by Patch Model metrics including the estimate of efficiency, the cv_E, the cv_D, the width of the dredge, and the EAS (Table 10). Low EAS (indicating more dredge overlap, low efficiency, or small experimental area), low efficiency estimates, high cv_E and cv_D, and smaller dredge sizes, along with experiments falling at or above the 80^{th} percentile for error estimates Err2, Err3, and Err4, fall on the positive (right) side of Dimension 1. High efficiency estimates, high EAS, larger dredge sizes, and low cv_E and cv_D fall on the negative (left) side of Dimension 1.

Dimension 2 (Fig. 7-8) is categorized by the species (ocean quahog and surfclam) and other variables relating to the location of the depletion experiments for the two species, such as depth, latitude, and region. The positive values are variables relating to ocean quahog depletion experiments, such as higher latitudes and deeper depths. Negative values are variables relating to surfclam depletion experiments: lower latitudes (Fig. 2) and shallower depths. Ocean quahog experiments were typically conducted further north (Fig. 1) than surfclam experiments and the species is generally found at deeper depths than surfclams. Dimension 3 (Fig. 8-9) is characterized by the cv_K, and high efficiency and high EAS fall on the positive side.

The parameters describing clam distribution do not fall on any axis and are grouped in the middle of the correspondence analysis graphs on all dimensions, therefore they are not included in the figures in order to improve clarity. Although clam distribution clearly affects the outcome of individual experiments as observed through simulation analysis (Poussard et al.

2021), this effect is distributed across the experimental spectrum, distributing uncertainty in a relatively random way with respect to the in-field experimental dataset.

Discussion

Forensics on Efficiency Estimates

The four error terms identify in-field depletion experiments that have attributes that engender misgivings as to their quality. Since the 4 metrics, cv_E, cv_K, OS, and average EAS used to generate two of the error estimates (Err1 and Err2) are orthogonal to each other, identification of a subset of experiments based on Err1 and Err2 suggests that these experiments are characterized by an unusual distribution of these 4 descriptive metrics. It is important to note that using a log transformation of EAS does not change the experiments that were flagged by these two error metrics. A close fit to the values of these 4 metrics was not found amongst the 9,000 simulations of Poussard et al. (2021) which covered a wide range of experimental protocols and field conditions of clam dispersion (Table 1). The absence of a close fit generates reason to suspect that these experiments may be uninformative or at least have produced inaccurate efficiency estimates. Error terms 3 and 4 (Err3 and Err4) relate to an inferred error in the efficiency estimates, also gleaned from comparison to the simulation dataset of Poussard et al. (2021). Experiments flagged by these error metrics were "most comparable" to simulations with high error in efficiency estimates based on the 4 described parameters, and potentially have high error in efficiency themselves. Nine out of ten experiments flagged by Err4 were also flagged by Err3, as these two metrics are very similar. These experiments may be uninformative or at least have produced inaccurate efficiency estimates. Ultimately, due to the forensic nature of the error terms, and the inability to evaluate all possible experimental conditions (e.g., all possible tow numbers, clam distributions, or all possible true efficiencies), the inference that the flagged experiments produced uninformative or inaccurate efficiency estimates cannot be affirmed. In aggregate, however, the evidentiary weight points to a subset of in-field experiments of lower quality than the remainder.

Interestingly, the experiments flagged by Err1, which might identify suspect experiments, exert less influence on the final objective of determining the efficiency of hydraulic dredges. The distribution of these experiments is unbiased relative to the remaining experiments, regardless of the metric used for comparison (Table 6). The same cannot be said for Err2, Err3, and Err4. The series of 16 depletion experiments that fall at or above the 80th percentile for Err2, Err3 and Err4 are shown to be clearly biased relative to the remaining experiments based on Wilcoxon rank sums tests (Table 8) and this bias is reinforced by correspondence analysis (Fig. 7-9). In addition, the direction of bias is noteworthy. Experiments identified by Err2, Err3, and Err4 are characterized by lower efficiency estimates on average, and their inclusion may bias the overall efficiency estimates used to inform stock assessments.

In correspondence analysis, Err2, Err3, and Err4 also fall on the same dimensional axis as a lower EAS value. Low EAS and low efficiency generally occur together, as the efficiency value is a variable in the equation determining EAS (Equation 3). The relationship is well-documented by Poussard et al. (2021). This expectation is confirmed in the in-field depletion experiment dataset by Pearson correlation (Fig. 5-6). EAS is also positively correlated with year for ocean quahog experiments, and with dredge width for both ocean quahog and surfclam experiments (Fig. 5-6). The relationship is driven by the largest dredge (3.81-m [12.5-ft]); experiments with this dredge size clearly demonstrating superior performance.

Higher OS in a depletion experiment does not always reduce uncertainty in Patch Model estimates. An explanation for this may come from the pragmatic efforts of a field experiment.

Depletion experiments are costly in vessel time and crew effort, often requiring more than 8 hours of nearly continual dredging. Cost at sea was sufficient that adaptive time management during the experiment was directed at limiting tow number, albeit with limited empirical guidance to determine the stopping point for the depletion experiment. One consequence of adaptive time management during the depletion experiment was a decision to add tows if the experiment appeared not to be generating a clear and consistent reduction in catch per tow. Correspondence analysis demonstrates the danger of the use of adaptive decisions during depletion experiments without rigorous empirical determining criteria designed to optimize the cost and benefit of increased tow number. The danger of terminating a depletion experiment early based on a potentially misleading depletion curve is present as well. The amount of overlap in dredge tows, OS, did not fall out cleanly in any of the dimensions on the correspondence analysis, the opposite of expectation based on the clear improvement afforded by higher tow numbers, and more tow overlap, in the simulation study of Poussard et al. (2021). However, the absence of OS does not diminish its effect on gear efficiency estimates in depletion experiments, but that its importance is unbiased relative to the variables establishing the dimensions. This is also true for the distribution of clams in space (e.g. NP, P, T, HP [Fig. 3]). Notably, both sets of variables, which in some fashion are measures of dredge overlap with tow paths or with clams in the area, are both relatively unbiased parameters; that is, they are not associated with any depth, dredge size, species, or other characteristic of the experiment. The distribution of clams relative to the distribution of tows is a critical constraint on efficiency estimation.

Correspondence analysis clearly reveals the relationships earlier identified by the Wilcoxon tests and by the Pearson correlations. The three error metrics, Err2, Err3 and Err4, which were shown to be highly significant in the Wilcoxon analyses fall on the positive side of

Dimension 1 along with the parameters and experiment characteristics significantly influenced by them. Err1, which did not demonstrate significant differences in the Wilcoxon tests, falls near the origin in all three dimensions, indicating that the experiments identified by this error estimate are more or less randomly distributed throughout the in-field depletion dataset. A tendency for larger dredges to be associated with improved experimental performance is seen in Figure 13; however, the influence of dredge size is complex as the various dredge sizes do not fall in order of size on Dimensions 1 or 2. Very likely, dredge size to some extent is conflated with other variables such as species, year, and depth, being determined more by boat availability and increased familiarity of the crew and scientific staff with depletion experiment methodology over time than experiment performance, with the clear exception of the largest dredge size. The fact that species falls near the origin on Dimensions 1 and 3 shows the similarity in efficiency estimates for the two species, which are separated essentially solely by depth.

In the correspondence analysis, Err2, Err3, and Err4 are associated with experiments characterized by smaller dredges, higher cv_E values, and higher cv_D values. These characteristics co-occurring instill suspicion as to the quality of the results obtained from a subset of the depletion experiments. Essentially, experiments falling at or above the 80th percentile for Err2, Err3, and Err4 are associated with experiments that have low efficiency estimates. Experiments most similar to simulations with high error in efficiency estimates were flagged by Err3 and Err4, indicating that these experiments could have high uncertainty in efficiency estimates themselves, strongly suggesting deletion of these experiments from further evaluation of the inherent efficiency of hydraulic clam dredges.

Estimation of Density

Interestingly, experiments with high cv_D are grouped with the low efficiency experiments identified by Err2, Err3, and Err4 in the correspondence analysis, indicating that experiments with more uncertain clam density estimates also produced low efficiency estimates and were flagged by the error metrics. Poussard et al. (2021) clearly show that the accuracy of efficiency estimates and the density of clams in the area are not correlated in simulated depletion experiments, save for instances where low clam density combines with an irregular distribution of clams in the benthos to bias efficiency low. Efficiency estimates not being influenced heavily by clam density is a logical outcome based on an expectation that hydraulic dredges should be equally efficient whether used in low-density or high-density regions. The apposition of high CV for the density estimate and low efficiency is likely a product of high uncertainty in the density estimate co-occurring with high uncertainty in the efficiency estimate. This could be indicative of an experiment design failing or environmental parameters not being conducive to estimating accurate and precise efficiency and density estimates.

The accuracy of the Patch Model density estimate was evaluated thoroughly in Hennen et al. (2012). The *k*-parameter was not evaluated for accuracy in that study because a negative binomial distribution was not used to create the distribution of clams. The *k*-parameter is indirectly related to the distribution of clams and tow distance (Hennen et al., 2012). The simulations of Poussard et al. (2021) show that the *k*-parameter estimates are higher with a uniform distribution of clams and lower with a more irregular distribution of clams. This parameter is influenced by the same conditions of the experiment that influence efficiency, but correspondence analysis does not cleanly separate the *k*-parameter or its CV from other variables such as the efficiency estimate, density estimate, depth, region, dredge width, and the cv_E and cv_D. (Fig. 8 and 9). Correspondence analysis identifies a tendency for low uncertainty in the *k*-parameter (the cv_K) to be associated with lower efficiency and higher cv_E, the same grouping of experiments that are flagged by the error terms.

Poussard et al. (2021) showed clearly that the dispersion of clams on the bottom can cause a decrease in performance in the depletion experiment. This outcome is exacerbated by low tow number and low amount of tow overlap. In practice, even an ideal experiment, with many dredge tows and a high degree of overlap in the tow paths, would appear to be susceptible to producing an unreliable efficiency estimate if the distribution of clams in the benthos is irregular. Clam dispersion is a random effect for the in-field experiments, despite its documented importance in determining outcomes. This is consistent with the fact that the locations for the experiments were chosen without any *a priori* knowledge of the local clam dispersion characteristics at the site. As Hennen et al. (2012) concluded, having divers or remote optical methods determine the size, location, and approximate density of clam aggregations would be useful in choosing the site and tow pattern in a depletion experiment.

Factors Affecting Field Outcomes

The size of the dredge is related to the efficiency estimated, with larger dredges being used with experiments with higher efficiency estimates. Smaller dredges were used in many experiments and these contributed disproportionately to the subset identified by error estimates Err2, Err3, and Err4 (Fig. 7). It may be that smaller dredges are harder to control precisely, which could lead to greater uncertainty in the exact position of the dredge, which can lead to error in the estimation of efficiency (Hennen et al., 2012; Willberg et al., 2013). The majority of flagged experiments identified by the four error estimates were conducted in 1997, 1999, and 2005, and among these experiments are those categorized as having lower efficiency estimates with more uncertainty in the estimate. Although speculative, two possibilities may be forwarded explaining this trend. A wider dredge may be inherently more efficient as loss in efficiency is likely associated with the encounter of clams near the lateral edges of the dredge knife blade, and these clams are a lower fraction of the potential catch with the larger dredge. In addition, the narrow dimension of the depletion rectangle was generally set at 10 dredge widths; thus, the larger dredge was used to deplete larger regions which may have reduced the influence of small-scale variations in clam dispersion within the depletion rectangle. It is noteworthy that experiments conducted with the largest dredge were in later years, when depletion experiment methodology was more consistent among experiments, and produced higher efficiency estimates, yielding higher OS measurements. Accordingly, the improved performance cannot unequivocally be assigned to the larger size of the dredge used.

Location of the depletion experiment might also affect the efficiency estimate. Ocean quahog depletion experiments conducted off Long Island have higher efficiency estimates than experiments conducted further south. The relationship is shown objectively (Fig. 1) and in correlation (Fig. 5). The correlation analysis does not show a significant relationship between latitude and the efficiency estimate, but this result accrues from the inclusion of high-efficiency surfclam experiments that took place further south (Fig. 2). The relationship is not associated with dredge width, although efficiency and dredge width are significantly correlated for ocean quahog experiments (Fig. 5). These experiments took place in deeper water, on the average, but correlation and correspondence analysis agree that depth, per se, does not influence outcomes. Edaphic factors may be examined as proxies for the influence of region, but little information is available to make a determination.

Depth might be considered to be an effective variable determining the success of a depletion experiment for hydraulic dredges as these dredges are operated using an onboard water pump attached to the dredge by means of a large hose. The vessel is less maneuverable in deeper water due to the increased amount of hose required to maintain an adequate scope while dredging. Surprisingly, neither correlation analysis nor correspondence analysis offers any evidence for a significant correlation between depth and experimental performance or the final efficiency estimate. Depth related variables, in fact, fall orthogonally to experiment performance metrics and error estimates Err2, Err3, and Err4 in correspondence analysis.

Conclusion

When 16 experiments (7 surfclam and 9 ocean quahog experiments) that fell at or above the 80th percentile for error estimates Err2, Err3 and Err4 are removed from the in-field depletion dataset, the mean efficiency estimate increased from 0.635 to 0.694 for surfclam experiments (Table 11). The median likewise rose substantially from 0.590 to 0.647 and the interquartile range, though remaining relatively unchanged in dimension, shifted to higher efficiency values. The mean efficiency estimate for ocean quahog experiments increased from 0.586 to 0.711, the median also rose from 0.629 to 0.667. The interquartile range was substantially reduced in dimension and also shifted to higher efficiency values. The efficiency estimates for the dataset after removal of experiments flagged by an error term are included to show that Err1 experiments do not have efficiency estimates that are biased in either direction and do not meaningfully negate the trends established by the other three error terms. Interestingly, the mean and median efficiency estimates for these hydraulic dredges targeting surfclams and ocean quahogs are nearly identical. Neither the species nor the presence of one generally in deeper water than the other significantly influences the overall efficiency which stands at approximately 70% regardless of mean or median determination.

The analyses of this paper permit the evaluation of the factors involved in defining a standard operating protocol for experiments of this kind which are inherently extremely expensive to conduct. Several metrics defining the success of the experimental design will likely be unknowns, such as the dispersion of clams on the bottom. As a consequence of the uncertainty behind these experiments, a sufficient number of replicates will always be required in order to provide a useful recommendation for catchability. Other studies of dredge calibration with a significant number of experiments (Hennen et al. 2012, Morson et al. 2018) come to effectively the same conclusion.

Patch Model estimates are useful to inform future stock assessment models, for example, capture efficiency estimates can be used to form prior distributions for catchability parameters (NEFSC, 2009, 2010a,b). However, these estimates are only as useful as the data from the depletion experiments used to inform the Patch Model. Three groups of experiments have significantly different efficiency estimates and CVs from the remainder, as shown by the Wilcoxon rank sums tests conducted on efficiency estimates flagged by Err2, Err3, and Err4.. Though these error estimates can only be used to infer experimental quality, they identify experiments with a range of questionable attributes which strongly implicate them as outliers biasing the efficiency estimates for the entire dataset. Removing these questionable experiments from the NMFS depletion dataset provides the best estimates of efficiency for these commercial hydraulic dredges and indicates that these are highly efficient dredges which minimize the degree of bottom contact relative to the catch.

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True Efficiency	0.9	0.6	0.2		
Clam Density (# m^{-2})	0.75	1.5	3.0		
Clam Distribution	NP	HP	P	T	
Number of Tows	40	25	20	15	10

Table 1: Metrics used in the simulation analysis block design of Poussard et al. (2021). All combinations of the four parameters were simulated: 50 simulations for each tetradic combination were conducted. Clam distribution is denoted as NP: uniform across the area, P: patches oriented across the narrow dimension, HP: patches oriented longitudinally, and T: patches of a triangular nature emanating from one side of the rectangle (see Figure 1).

Depletion Experiment OQ08-02: estimated efficiency: 0.79507							
			CV Efficiency	CV *k* parameter	EAS (ft^2)		
Simulations' Average Values			5.477	41.966	229606.0		
Values from OQ08-02			9.361	35.067	264843.7		
Mean Absolute Error Estimate			0.1003	Range	0.0001-0.4		
Error in Efficiency Estimate	Density (#/m^2)	Clam Distribution	True Efficiency	CV Efficiency Estimate	CV *k* Parameter	EAS (ft^2)	
0.6667	0.75	HP	0.6	0.009	38.4412	243287.3	
0.6667	1.5	HP	0.6	0.009	38.6189	243287.3	
0.6667	3	HP	0.6	0.019	37.5421	245107	
0.1517	0.75	P	0.6	13.4774	47.8368	242744.3	
0.0633	0.75	P	0.6	14.3416	46.6667	244304.5	
0.15	0.75	P	0.6	7.3768	47.6762	247782.9	
0.105	1.5	P	0.6	9.4721	46.1634	243845.6	
0.0633	1.5	P	0.6	6.3793	47.7372	244304.5	
0.0883	1.5	P	0.6	5.4058	47.5397	247782.9	
0.6667	0.75	T	0.6	0.071	41.7476	243287.3	
0.6667	0.75	T	0.6	0.02	41.2644	245107	
0.6667	1.5	T	0.6	0.019	41.018	245107	
0.6667	3	T	0.6	0.121	41.6268	243287.3	
0.0905	0.75	NP	0.6	5.7007	42.9225	221701.2	
0.0572	0.75	NP	0.6	4.992	41.7308	223632.1	
0.0359	0.75	NP	0.6	6.4963	40.6921	222596.4	
0.0778	0.75	P	0.6	7.6546	48.6502	221701.2	
0.0017	0.75	P	0.6	6.5863	48.5524	223970.1	

0.0483	3	P	0.6	7.0053	38.5597	223970.1

Table 2: Parameters for 19 simulations that best compared to the depletion experiment OQ08-02. Clam distribution is denoted as NP (uniform), P (vertical bands), HP (clams in half the area), and T (diagonal across the area). See Figure 3.

SC04-01: estimated efficiency: 0.53334						
		CV Efficiency		CV *k* parameter	EAS (ft^2)	
Simulations' Average Values		14.564		25.703	176994.1	
Values from SC04-01		19.8354		28.0845	138041.61	
Mean Absolute Error Estimate		0.1471		Range	0 – 0.5817	
Error in Efficiency Estimate	Density (#/m^2)	Clam Distribution	True Efficiency	CV Efficiency Estimate	CV *k* Parameter	EAS (ft^2)
0.3083	1.5	HP	0.6	24.2038	26.5866	203787
0.2533	1.5	HP	0.6	26.1968	26.7742	206081.5
0.425	3	HP	0.6	27.2515	26.4758	203975.6
0.4633	3	HP	0.6	18.3371	26.422	203780.9
0.4133	3	HP	0.6	18.75	26.8293	201607.8
0.2533	0.75	T	0.6	19.016	28.5385	202525.9
0.445	0.75	T	0.6	14.9942	28.6364	203780.9
0.325	0.75	T	0.6	13.2075	28.5484	200008.7
0.2233	1.5	T	0.6	19.2098	28.5821	202525.9
0.3467	1.5	T	0.6	19.9257	28.7838	203348.4
0.0867	1.5	T	0.6	23.6196	28.9172	201607.8
0.0033	3	T	0.6	23.4114	28.882	203787
0.34	3	T	0.6	19.9005	28.8194	203348.4
0.4167	3	T	0.6	14.7059	28.0702	201909.8
0.0317	1.5	NP	0.6	1.7609	25.3618	146398.1
0.025	1.5	NP	0.6	1.3886	26.9719	147346.4
0.0083	3	NP	0.6	1.3091	24.6763	147972.6
0.0383	0.75	P	0.6	2.4398	26.3924	145011.1
0.0233	1.5	P	0.6	2.2964	25.07	145011.1

Table 3: Parameters for 19 simulations that best compared to the depletion experiment SC04-01. Clam distribution is denoted as P (vertical bands), HP (clams in half the area) and T (diagonal across the area). See Figure 3.

Correspondence Analysis Legend			
Patch Model Outputs		Species	
E1, E4	Efficiency	O	Ocean quahog
D1, D4	Density	S	Surfclam
K1, K4	*k* parameter	Region	
C1, C4	CV Efficiency	LI	Long Island
N1, N4	CV Density	NJ	New Jersey
P1, P4	CV *k* parameter	DMV	Delmarva
Experiment Descriptors		Error Terms	
S1, S4	EAS	R12	Err1
T1, T4	OS	R22	Err2
L1, L4	Latitude	R32	Err3
Z1, Z4	Depth	R42	Err4
8.33, 10, 10.83, 12.5	Dredge Widths		

Table 4: Variables used in correspondence analysis. Error estimates were entered as supplementary variables (Clausen 1998). E,D,K,C,N,P,S,T,L, and Z were entered as quartiles; only quartiles 1 and 4 are shown in the graphs. Error estimates were entered as 1 (below the 80^{th} percentile) or 2 (at or above the 80^{th} percentile).

Ocean Quahog (N=19)					
	Efficiency	Density (#/m²)	*k* Parameter	EAS (ft²)	Tow Number
Mean	0.586	1.184	7.724	116701.2	17.433
Median	0.629	0.094	6.165	92941.7	17.270
Standard Deviation	0.113	0.646	3.045	93141.1	3.713
Coefficient of Variance	0.357	16.907	0.613	0.798	0.189
Surfclam (N=31)					
	Efficiency	Density (#/m²)	*k* Parameter	EAS (ft²)	Tow Number
Mean	0.635	1.496	12.097	146077.2	22.330
Median	0.590	0.738	5.689	78852.3	19.143
Standard Deviation	0.131	1.786	3.011	157727.1	5.829
Coefficient of Variance	0.206	12.855	0.351	1.121	0.193

Table 5: Mean, median, mean standard deviation as estimated by the Patch Model, the effective area swept (EAS), the number of tows, and the mean CV for depletion parameters efficiency, density, and *k* parameter for the 50 field depletion experiments. The standard deviation and CV values for efficiency and density are the averages of the delta method uncertainties associated with patch model parameter estimation.

Experiment ID	Region	Dredge Width(ft)	Tows	OS	Year	Latitude	Longitude
SC1997-2(*3,*4)	NJ	8.33	39	0.5237	1997	40.05317	-73.83917
SC1997-3	NJ	10.83	13	1.2586	1997	39.39317	-73.91033
SC1997-4 (*1)	NJ	10.83	18	0.9197	1997	39.39317	-73.91033
SC1997-5	NJ	8.33	17	0.7535	1997	39.365	-73.89833
SC1997-6 (*1)	NJ	8.33	19	0.6972	1997	39.365	-73.89833
SC1999-2	NJ	10.83	4	1.4151	1999	39.68133	-73.74667
SC1999-3 (*2)	NJ	10.83	5	1.1389	1999	39.68133	-73.74667
SC1999-4	NJ	10.83	6	1.7098	1999	39.52133	-73.77867

SC1999-5 (*1)	DMV	10.83	28	0.7257	1999	36.902	-74.97583
SC1999-6 (*2)	NJ	10.83	4	1.1338	1999	39.56333	-73.91167
SC1999-7	NJ	10.83	10	0.7994	1999	39.768	-73.91633
OQ00-01 (*2)	LI	12.5	22	0.6107	2000	40.60217	-71.9875
OQ00-02 (*1)	LI	12.5	16	0.6647	2000	40.3945	-72.543
OQ00-03 (*2,*3,*4)	LI	10	27	0.4191	2000	40.583	-72.79683
OQ02-01(*3,*4)	LI	10	24	0.7954	2002	40.72762	-71.7373
OQ02-02	LI	10	22	0.6755	2002	40.10312	-73.19108
OQ02-03	NJ	10	20	0.7304	2002	38.81491	-73.81335
OQ02-04 (*3*4)	DMV	10	24	0.7645	2002	37.88755	-74.64486
SC02-02	NJ	10.83	16	0.7788	2002	40.10908	-73.84423
SC02-03 (*3*4)	NJ	10.83	20	1.0199	2002	39.26923	-73.78116
SC02-04	DMV	10.83	18	0.7992	2002	38.85791	-74.02778
SC04-01	NJ	10	24	0.9250	2004	39.28611	-73.87778
SC04-02	NJ	10	20	0.8534	2004	39.58278	-74.02778
SC04-03 (*1)	DMV	10	20	1.0088	2004	38.27075	-74.3792
OQ05-01 (*1*2*3*4)	LI	10	20	1.2952	2005	40.51903	-72.07617
OQ05-02 (*1)	LI	10	21	1.3401	2005	40.38957	-72.3895
OQ05-03 (*2*3*4)	LI	10	20	1.1380	2005	40.6422	-72.6517
OQ05-04 (*2)	LI	10	17	1.1259	2005	40.6817	-72.18147
OQ05-06 (*2*3*4)	LI	10	20	1.0803	2005	40.0555	-72.41673
SC05-01	NJ	10	20	1.1754	2005	39.2653	-74.37947
SC05-02	NJ	10	17	1.0985	2005	39.56383	-73.90364
SC05-03(*1*2)	NJ	10	20	1.0094	2005	39.89733	-73.90591
SC05-04 (*3*4)	DMV	10	20	1.2129	2005	39.56972	-73.54946
SC05-05	NJ	10	17	1.0779	2005	39.43615	-73.3732
OQ08-01	LI	12.5	17	0.8493	2008	40.93762	-72.04765
OQ08-02	LI	12.5	17	0.8783	2008	40.27445	-72.84397
OQ08-03	SNE	12.5	17	0.7940	2008	41.02307	-70.85472
SC08-01	NJ	12.5	13	0.8097	2008	39.30475	-74.05158
SC08-02	NJ	12.5	18	1.2103	2008	39.18136	-74.07645
SC08-03 (*1)	NJ	12.5	21	0.8772	2008	39.60343	-73.42194
SC08-04	NJ	12.5	17	0.9867	2008	39.81033	-73.9149
SC08-09	NJ	12.5	17	0.9607	2008	39.31328	-74.05285

OQ11-01 (*2)	NJ	12.5	10	1.0210	2011	39.03003	-74.05774
OQ11-02	NJ	12.5	20	0.9027	2011	39.89356	-73.48104
OQ11-02S	NJ	12.5	18	1.1519	2011	39.8925	-73.475
OQ11-05	LI	12.5	22	0.9783	2011	40.13542	-72.1201
SC11-02 (*4)	NJ	12.5	20	0.9027	2011	39.89356	-73.48104
SC11-02S	NJ	12.5	18	0.9543	2011	39.8925	-73.475
SC11-03 (*1)	LI	12.5	14	1.0206	2011	40.567	-73.081
SC11-04	LI	12.5	17	0.9260	2011	40.641	-73.036

Table 6: Metrics for in-field depletion experiments targeting ocean quahogs and surfclams between 1997 and 2011. Region is identified as LI - Long Island, NJ - New Jersey, SNE - Southern New England, DMV - Delmarva. Experiments found falling at or above the 80th percentile for each error estimate are denoted with an asterisk (*) followed by the number of the error estimate (1,2,3,4).

	Number flagged	Efficiency	Eff SD	Eff CV	Density (# m^{-2})	Dens SD	Dens CV	*k Parameter*	*k SD*	*k CV*	EAS (ft^2)	OS
Err1 Average	10	0.514	0.12	26.8	2.26	0.49	214.34	5.41	2.57	88.6	1075010	0.96
Err1 Median		0.567	0.12	24.06	0.67	0.13	193.92	4.52	1.99	32.24	152803	0.96
Err2 Average	10	0.464	0.17	134.74	1.36	5.82	3933.21	20.94	2.91	59.22	1068334	1
Err2 Median		0.551	0.11	25.3	0.88	0.23	189.55	6.68	2.24	31.95	114811	1.1
Err3 Average	9	0.384	0.11	34.09	1.51	0.36	292.3	5.3	2.1	58.5	70873	0.92
Err3 Median		0.381	0.1	32.08	0.97	0.36	238.35	4.45	1.58	29.87	67840	1.02
Err4 Average	10	0.419	0.1	31.92	1.15	0.33	273.36	5.34	2.07	55.78	87557	0.92
Err4 Median		0.435	0.1	27.39	0.92	0.32	205.66	5.07	1.62	29.91	68891	0.96

Table 7: Average and median values for depletion experiment parameters for the experiments falling at or above the 80th percentile for each error estimate. Efficiency SD, Density SD, and *k* parameter SD are Patch Model metrics from the maximum likelihood equation (Eq 5). CV metrics are calculated using Eq 6.

	Err1	Err2	Err3	Err4
Variable	Pr > |Z|	Pr > |Z|	Pr > |Z|	Pr > |Z|
Efficiency	-	0.0454	0.0004	0.0014
Efficiency CV	-	-	0.018	-
Density	-	-	-	-
Density CV	-	-	0.025	-
k Parameter	-	-	-	-
k Parameter CV	-	-	0.034	0.025
EAS	-		0.0001	0.0009
Tows	-	-	-	-

Table 8: Wilcoxon Rank Sums test results for depletion experiment variables classified by error terms. Nonsignificance (α≤0.05) is denoted by a dash (-).

	Err 2		Err3		Err4	
	< 80th Percentile	≥ 80th Percentile	< 80th Percentile	≥ 80th Percentile	< 80th Percentile	≥ 80th Percentile
Efficiency						
Mean	0.654	0.464	0.667	0.384	0.666	0.419
Median	0.645	0.551	0.652	0.381	0.652	0.435
CV Efficiency						
Mean	19.496	134.744	44.402	34.089	45.202	31.920
Median	19.232	25.299	16.789	32.075	17.325	27.392
CV *k*-parameter						
Mean	41.785	59.215	42.368	58.497	42.644	55.783
Median	32.924	31.953	33.139	29.869	33.257	29.913
Density (# m^{-2})						
Mean	1.389	1.356	1.345	1.507	1.367	1.421
Median	0.743	0.887	0.743	0.969	0.743	0.915
CV Density						
Mean	162.998	3933.081	1054.153	292.294	1077.931	273.350
Median	135.765	189.542	132.375	238.345	132.924	205.655
OS						
Mean	0.948	0.997	0.967	0.917	0.969	0.915

Median	0.911	1.103	0.926	1.020	0.940	0.961
EAS Mean	194273.5	1068334.2	434547.0	70873.0	439467.7	87557.2
Median	166725.7	114811.3	172934.9	67840.8	172768.5	68891.7

Table 9: A comparison of mean and median estimates of depletion parameters between experiments above and below the 80th percentiles for error terms Err2, Err3, and Err4

Dimension 1			Dimension 2			Dimension 3		
Variable	Negative (<-0.5)	Positive (>0.5)	Variable	Negative (<-0.5)	Positive (>0.5)	Variable	Negative (< -0.5)	Positive (>0.5)
Dredge Width	12.5	8.33, 10.83	Dredge Width	10.83	N/A	Dredge Width	10.83	N/A
Efficiency	High	Low	OS	N/A	Low	Efficiency	N/A	High
CV Efficiency	Low	High	Species	Surfclam	Ocean Quahog	EAS	N/A	High
EAS	High	Low	EAS	N/A	Low	CV *k* Parameter	High	N/A
CV *k* Parameter	N/A	Low	Region	NJ	LI			
Err2, Err3, Err4	N/A	High	Depth	Low	High			
CV Density	Low	High	Latitude	N/A	High			
Region	N/A	DMV	CV Density	N/A	Low			

Table 10: Variables that fall on each of the 3 dimensions with loading factors ≤ -0.5 or ≥ 0.5 according to the correspondence analysis.

		Mean	Standard Deviation	1st Quartile	Median	3rd Quartile
Ocean Quahog	Efficiency Estimates (All Experiments)	0.586	0.260	0.381	0.629	0.779
	Efficiency Estimates (9 flagged by Err 2,3,4 removed)	0.711	0.195	0.629	0.667	0.795
	Efficiency Estimates (10 flagged by all Error terms removed)	0.758	0.169	0.641	0.716	0.898
Surfclam	Efficiency Estimates (All Experiments)	0.635	0.229	0.533	0.590	0.779

	Efficiency Estimates (7 flagged by Err 2,3,4 Removed)	0.694	0.196	0.570	0.647	0.852
	Efficiency Estimates (13 flagged by all Error terms removed)	0.738	0.172	0.584	0.733	0.889

Table 11: Comparing mean, SD, median, and quartiles for all 19 ocean quahog and 31 surfclam depletion experiments with the dataset after 16 experiments at or above the 80th percentile for error terms Err2, Err3, and Err4 were removed.

Figure Captions

Figure 1: Locations of the 19 depletion experiments targeting ocean quahogs off the east coast of the US. Colors indicate Patch Model efficiency estimates for each depletion experiment. Boundaries on the continental shelf shown as thick lines represent the regions used for various analyses in stock assessments. Thin lines are depth contours.

Figure 2: Locations of the 31 depletion experiments targeting surfclams off the east coast of the US. Colors indicate Patch Model efficiency estimates for each depletion experiment. Boundaries on the continental shelf shown as thick lines represent the regions used for various analyses in stock assessments. Thin lines are depth contours.

Figure 3: Clam distributions from the simulation analysis in Poussard et al. (2021) with dredge tow paths, the straight colored lines, passing through the area. Colors denote the amount of overlap (number of hits) in the dredge paths. Dots are clams. Top left: a biased clam distribution with highest densities in half the area (HP). Bottom left: clams distributed in even vertical bands (P). Bottom right: not-patchy, clams distributed relatively uniformly (NP). Top right: clams distributed in a triangle wedge from south west to north east across the area (T).

Figure 4: Efficiency estimates with standard deviations for the 31 depletion experiments targeting Atlantic surfclams (left) and the 19 depletion experiments targeting ocean quahogs (right). Black horizontal line indicates the mean efficiency for all for the respective groups of experiments.

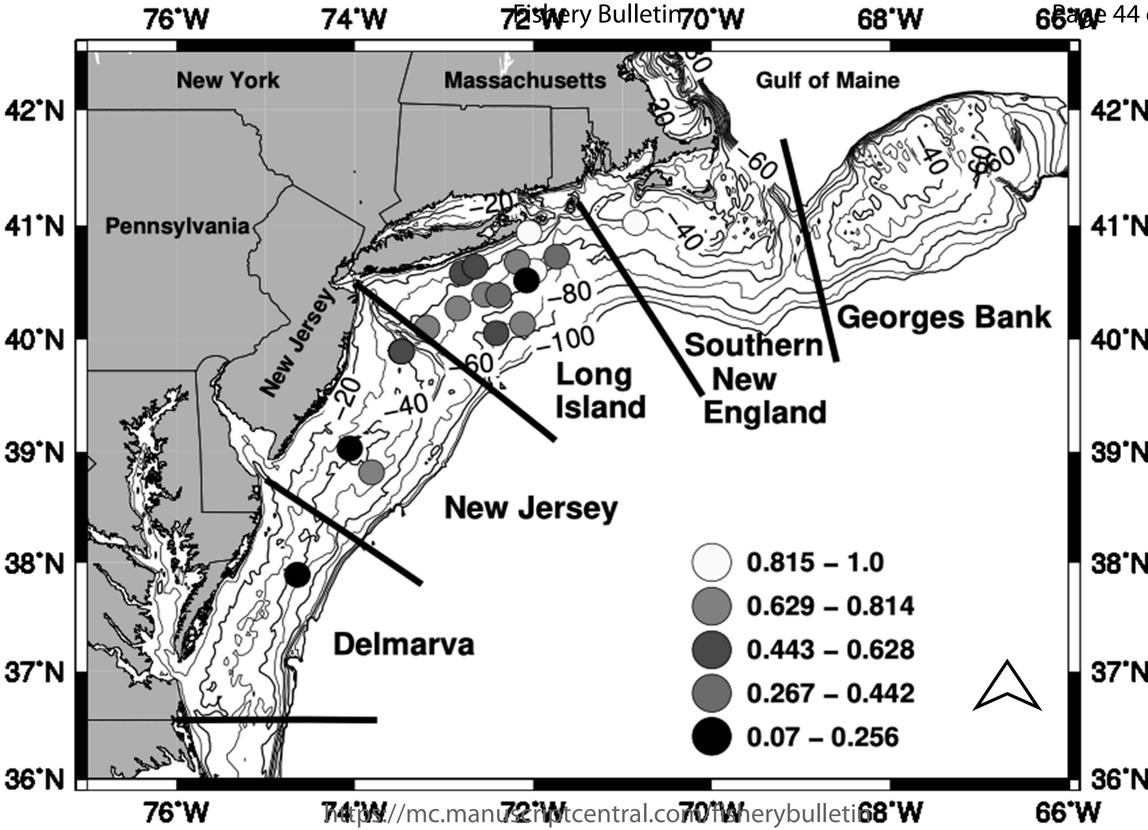
Figure 5: Correlogram for experiments targeting ocean quahogs. Numbers in the squares are Pearson's correlations. Significant correlations ($\alpha \leq 0.05$) are denoted by gray circles. Positive correlations are dark gray; negative correlations are light gray.

Figure 6: Correlogram for experiments targeting surfclams. Numbers in the squares are Pearson's correlations. Significant correlations ($\alpha \leq 0.05$) are denoted by gray circles. Positive correlations are dark gray; negative correlations are light gray.

Figure 7: Correspondence analysis for dimensions 1 and 2 for the depletion dataset. Error terms were entered as supplementary variables (Clausen 1998). E,D,K,C,N,P,S,T,L, and Z were entered as quartiles; only quartiles 1 and 4 are shown in the graphs. Dredge widths are entered as the widths in feet. Error estimates were entered as 1(below the 80th percentile) or 2 (at or above the 80th percentile). Gray box demarcates the area from -0.5 to 0.5 on the x and y axes.

Figure 8: Correspondence analysis for the depletion dataset for dimensions 2 and 3. Error terms were entered as supplementary variables (Clausen 1998). E,D,K,C,N,P,S,T,L, and Z were entered as quartiles; only quartiles 1 and 4 are shown in the graphs. Dredge widths are entered as the widths in feet. Error estimates were entered as 1(below the 80th percentile) or 2 (at or above the 80th percentile). Gray box demarcates the area from -0.5 to 0.5 on the x and y axes.

Figure 9: Correspondence analysis for dimensions 2 and 3 for the depletion dataset. Error terms were entered as supplementary variables (Clausen 1998). E,D,K,C,N,P,S,T,L, and Z were entered as quartiles; only quartiles 1 and 4 are shown in the graphs. Dredge widths are entered as the widths in feet. Error estimates were entered as 1(below the 80th percentile) or 2 (at or above the 80th percentile). Gray box demarcates the area from -0.5 to 0.5 on the x and y axes.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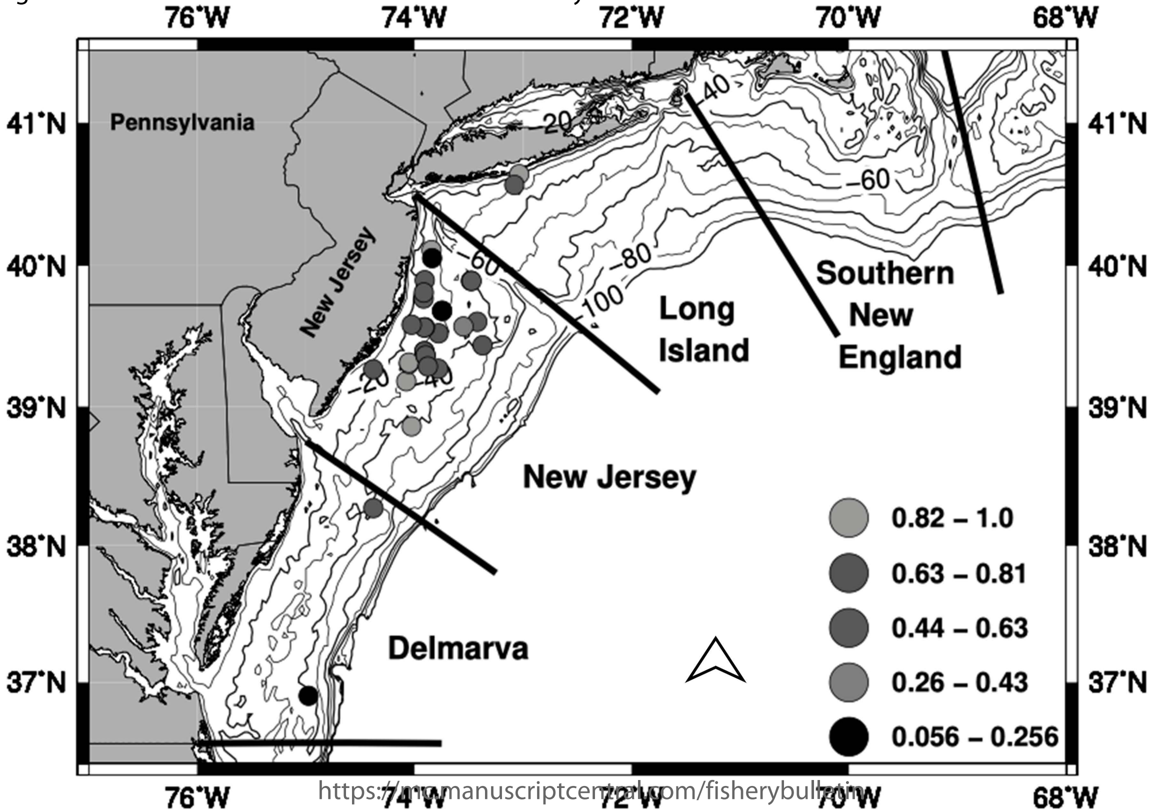
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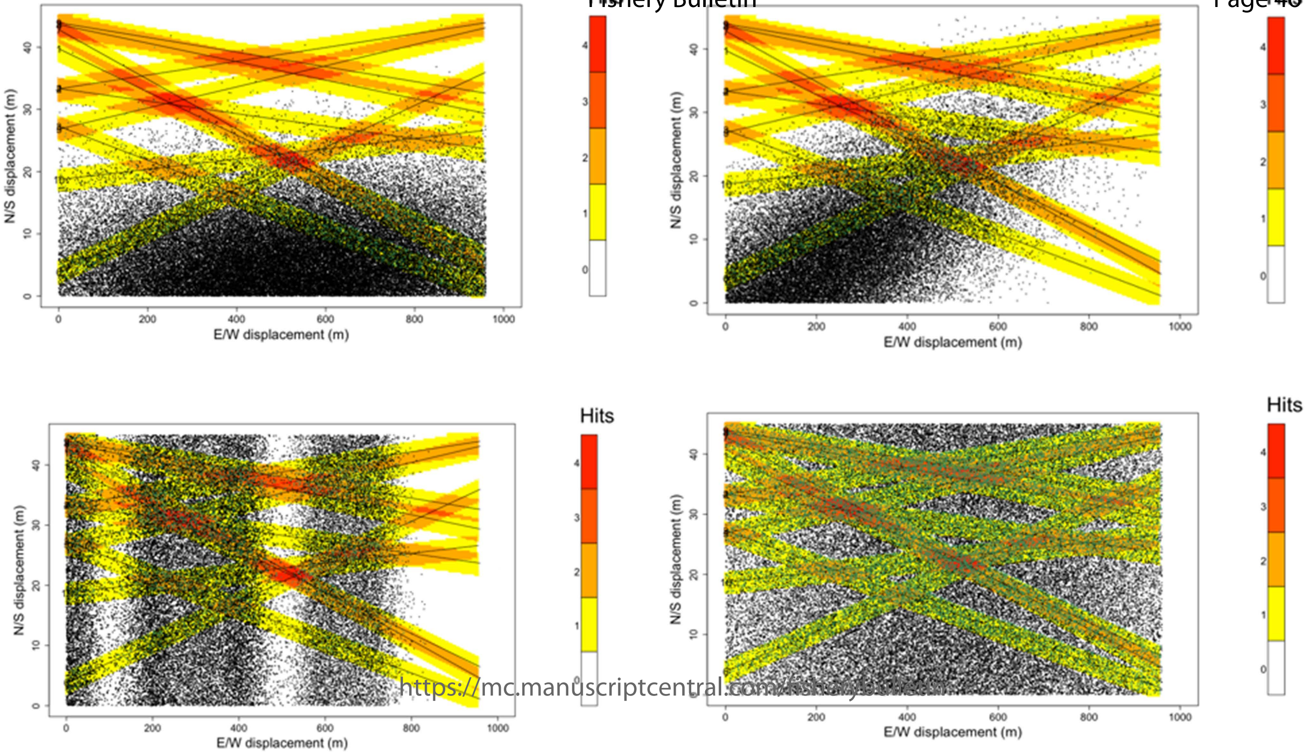
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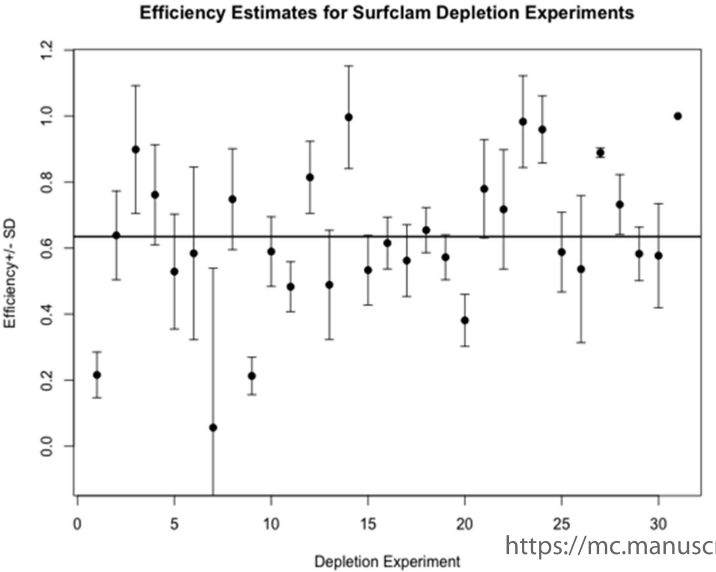
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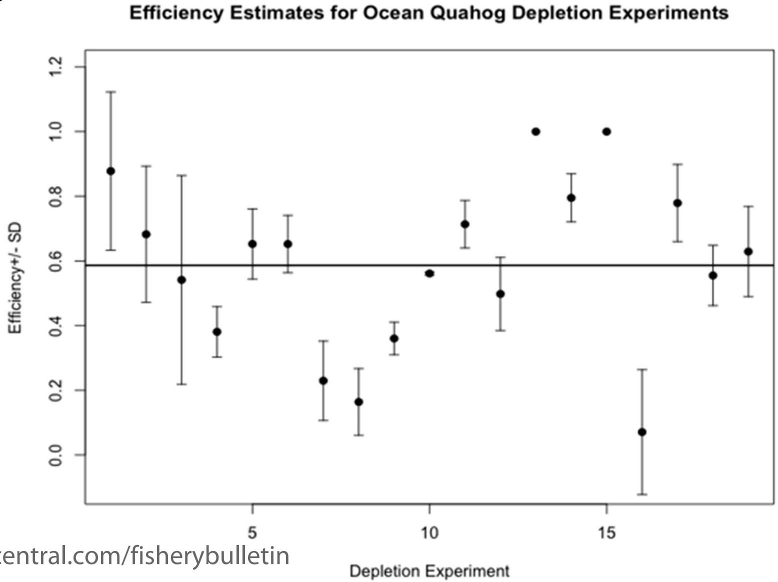
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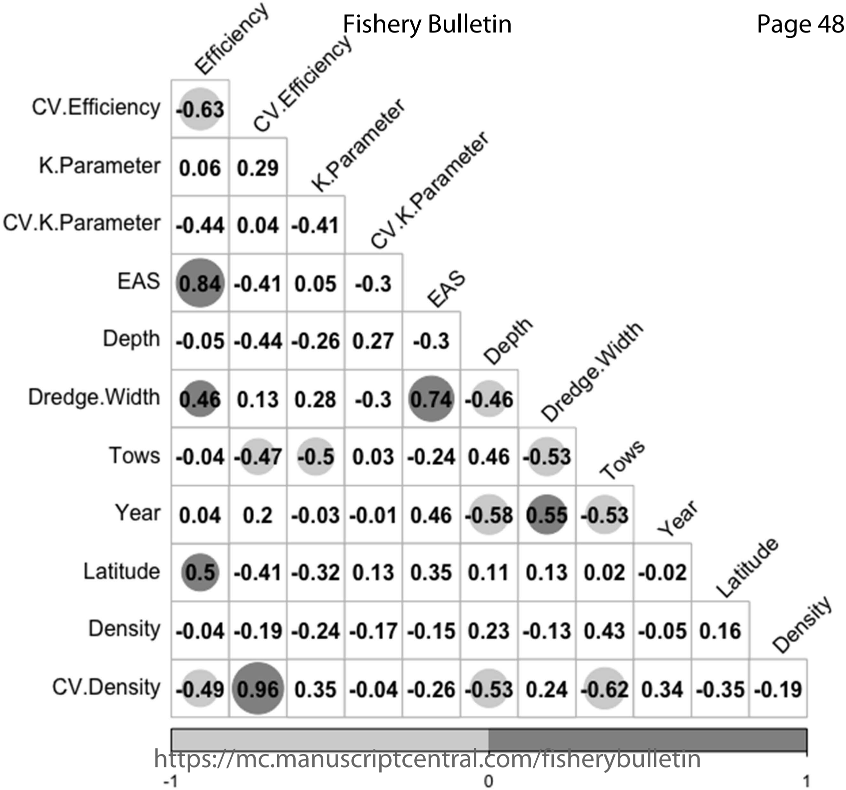
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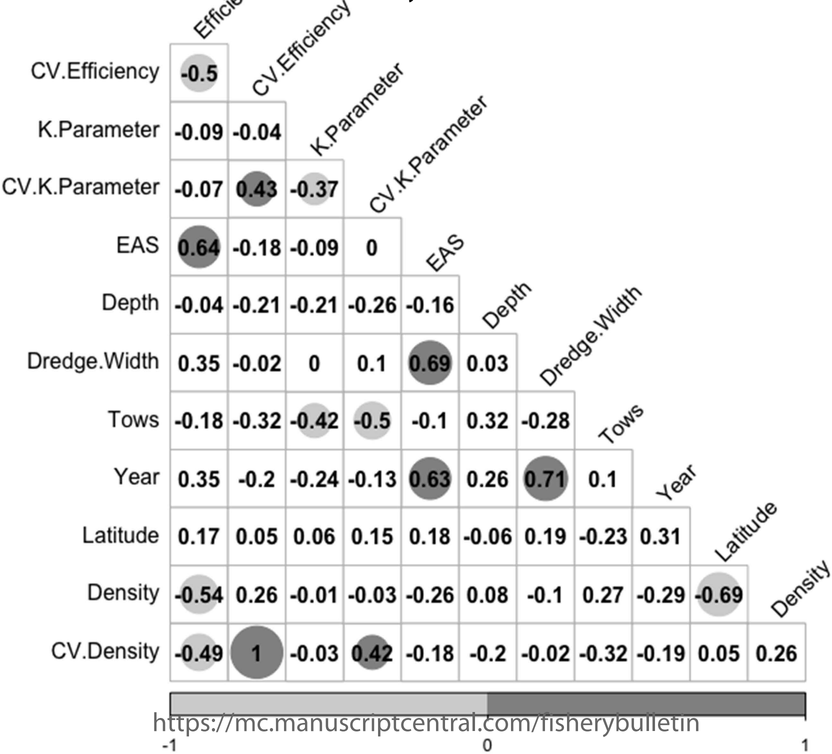
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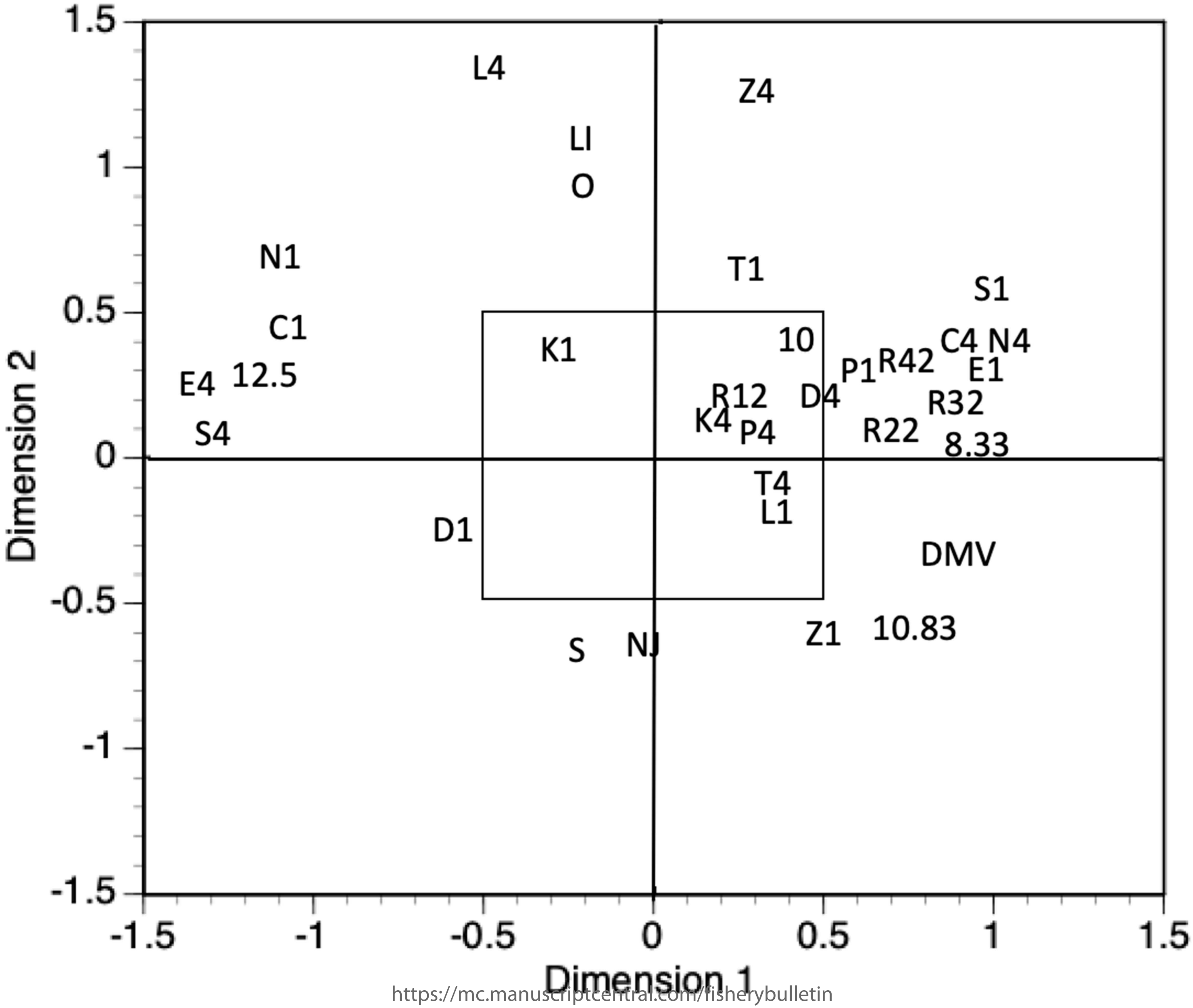
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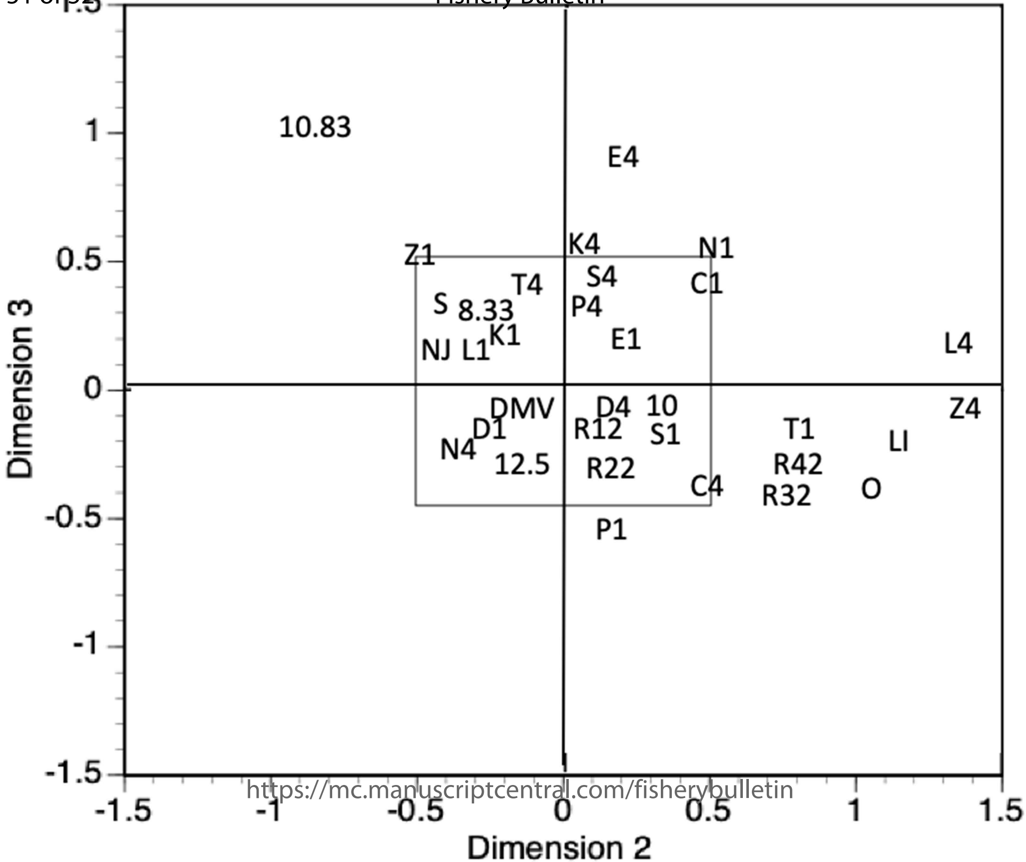
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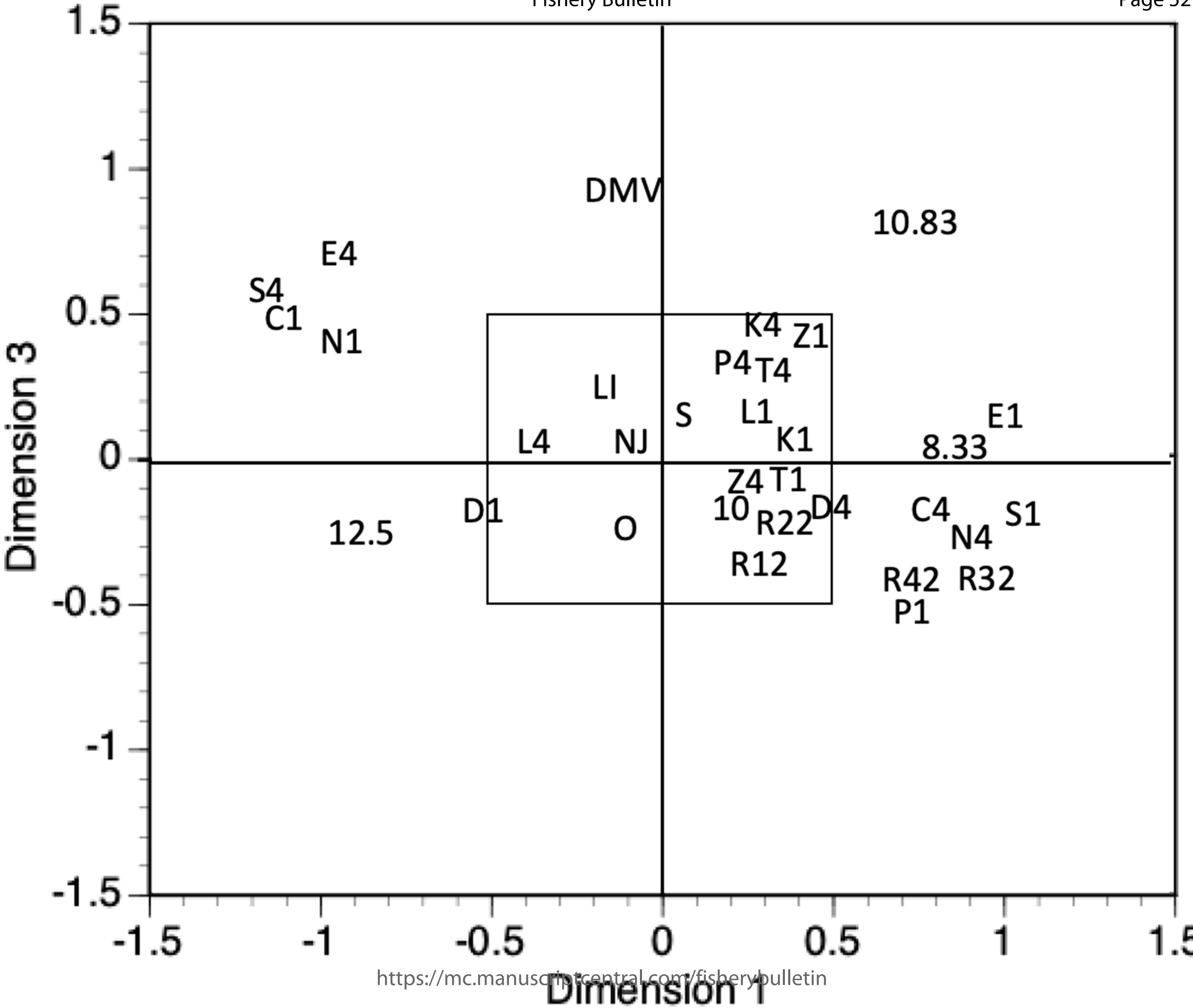
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