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Authors: Powell, Eric N., Klinck, John M., and Poussard, Leanne M.

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THE “CHALLENGE” OF DEPLETION: WHY THE OYSTER FISHERY IS NOT SELF-REGULATING

ERIC N. POWELL,[1]* JOHN M. KLINCK[2] AND LEANNE M. POUSSARD[1]
[1]*Gulf Coast Research Laboratory, University of Southern Mississippi, 703 East Beach Drive, Ocean Springs, MS 39564;* [2]*Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, Norfolk, VA 23529*

ABSTRACT The possibility that the economics of the oyster fishery impose a self-limitation on overharvesting has been proffered on occasion. The inefficiency of harvesting by the fishery has been evaluated and estimates of the exploitation rate permissible under conditions of maximum sustainable yield have been obtained in previous studies. The question becomes to what extent does the inefficiency of harvest interact with the economics of the fishery to compromise ready detection of overfishing? This study explores the possibility that the constraint of economics on the fishery occurs at oyster exploitation rates that are higher than maximum sustainable yield, leading ineluctably to overfishing if unconstrained and to the appearance of unduly limited fishing if properly constrained. A model is developed that simulates oyster harvesting by dredging. This model tracks vessel behavior and fishery performance in economic terms (CPUE) under varying stock densities and dredge efficiencies. Simulation results show that stock density and on-deck culling speed have the strongest effect on time required, profitability, and effectiveness of harvest, whereas dredge efficiency has a lesser influence. Evaluation of simulations shows that overfishing occurs at a stock density that provides near-optimal economic returns. The oyster fishery does not perceive a decline in the stock under sustainable conditions, as the on-deck processing capacity enables the catch rate to remain relatively stable until the stock declines well below sustainable levels. The consequence of setting fishing regulations such that a decline in catch is perceived is to assure routine and substantive overfishing, thereby creating a potential conflict between apparent and real sustainability. This conflict may explain the inability of state regulatory authorities to impose limitations consistent with long-term resource stability. The perception that a decline in the rate of catch should be observed under standard effort-based regulatory controls is a principal challenge that must be overcome if sustainability is to become normative in the U.S. oyster fishery.

KEY WORDS: oyster, *Crassostrea,* fishery economics, dredge efficiency, vessel operation, sustainable management

INTRODUCTION

Sustainable management of the fishery for the eastern oyster *Crassostrea virginica* has been elusive. Part of the challenge accrues from the unique necessity of managing the shell bed and the live animal, as the relatively short half-life of oyster shells (Powell et al. 2006, Soniat et al. 2012, Pace et al. 2020) necessitates continual input of shell from the living community (Mann & Powell 2008, Powell et al. 2012, 2018, Soniat et al. 2019). Nonetheless, estimates of the exploitation rate permissible under conditions of maximum sustainable yield have been obtained (Powell et al. 2018). The possibility that the economics of the oyster fishery impose a self-limitation on overharvesting has been proffered on occasion, and the likelihood that economics often drive regulatory decisions rather than biological reference points is substantial. The inefficiency of harvesting by the fishery has been evaluated (Banta et al. 2003) and possibly leads to: a false inference about stock status. The question becomes to what extent does the inefficiency of harvest interact with the economics of the fishery to compromise ready detection of overfishing?

The economics of the oyster fishery have been variously evaluated, from the standpoint of the market structure (Wirth & Minton 2004), the trade-off with ecosystem services (Kasperski & Wieland 2010), the influence of *Vibrio* on consumer demand (Keithly & Diop 2001), and the influence of area management (Santopietro et al. 2009). A detailed evaluation of the performance of the fishery under standard operations with respect to oyster abundance, removal efficiency, and fishery reference points [e.g., fishing mortality rate at maximum sustainable yield (F_{msy})] has not yet occurred, however, although the influence of harvesting inefficiency in limiting production has been considered (Agnello & Donnelley 1975), the single exception being a field experiment conducted by Menzel and Hopkins (1952) which suggested that an economic limit is reached with a stock reduction of about 60%.

Here, we use a model to simulate the oyster fishery from the point of view of the efficiency at which the fishery can deplete the oyster resource and evaluate the influence of factors such as oyster density, dredge efficiency, on-deck processing capacity, and ex-vessel value on the outcome. We focus our simulations on the fishery as it exists on public grounds as a direct-market fishery in which market-size oysters destined for direct sale are culled and sacked while fishing. The direct-market fishery has been the focus of numerous modeling efforts aimed at determining conditions under which the removals are sustainable. These have included the stock alone (see review in Powell et al. 2018) or in combination with the shell resource (Soniat et al. 2012, 2014, 2019). Much less attention has been paid to modeling the fishing activity itself as it interacts with the availability of the stock on the public ground and the economics of the fishing process thereon, although such considerations have been considered for a number of other fisheries (e.g., Dorn 1998, 2001, Hutton et al. 2004, Millischer & Gasuel 2006). The simulations to follow are designed to help rectify this deficiency.

MATERIALS AND METHODS

Model Overview

The model simulates the removal of oysters from a reef through dredging. The dredging procedure mimics a standard

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*Corresponding author. E-mail: eric.n.powell@usm.edu

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approach to fishing widely used among oystermen along the U.S. East and Gulf coasts in which the dredge is deployed from the starboard and/or port side of a boat and towed in an arcuate path at slow speed. Periodically, the dredge is lifted to the boat and its contents dumped for culling, after which the dredge is returned to the water. While the most recent haul is culled, the dredge is again dragged slowly in an arcuate path. The sacking rate often is determined by the length of time to cull oysters on the boat, particularly when oyster abundance is high, and by the efficiency of capture when oyster abundance is low.

The model assumes that the captain will seek out areas of high abundance to fish. When such a location is identified, a pole or other marker is deployed to orient the path of the boat (Frey et al. 2018). When the local resource declines enough, the oysterman will stop dredging, pull the pole, seek out another location to fish, deploy the pole again, and again commence fishing.

Catch is recorded as the number of sacks or bushels of oysters obtained per hour on site. Given a price per sack for oysters, a specified number of hours oystering, and a cost per day for a fishing trip, the oysterman can decide when the dredging is no longer cost-effective.

Model Domain and Stock Setup

The boundary of the oyster reef or bed is described by a polygon defined by a set of corner points connected with straight line segments. The location of the corners is provided in X–Y units. A grid of square cells (2 m on a side) is defined to cover the reef. At the beginning of a simulation, all cells are assigned an oyster density defined as market-size oysters m^{-2}. For convenience, initial density in the simulations considered here is uniform across the domain. The model domain is 172 × 132 m, an area of approximately 2.27 hectares (~5.61 acres). This is a relatively small area workable by a single vessel (e.g., Powell et al. 2001).

Vessel, Gear, and Performance

The width of the dredge, the speed of the boat during dredging, and the duration of a tow are held constant for all simulations. These choices produce a standard tow distance. The inherent efficiency of the dredge, defined here as a dredge that is not overfull (Powell et al. 2002), a condition which reduces catch efficiency (Powell et al. 2001, Banta et al. 2003, Powell & Ashton-Alcox 2004), is stipulated. Dredge-induced mortality is assumed to be inconsequential (Powell et al. 2001).

The dredging operation is delineated as a series of focused fishing efforts oriented about a fixed position designated by the placement of a pole or buoy. Pole placement is randomly chosen from all grid cells containing an oyster density higher than the average oyster density over the reef. The time taken for this search is not added to the total time elapsed during the fishing process, as this may vary widely based on the knowledge of the captain, oyster density, and oyster distribution. The time spent searching and degree of improvement in fishing performance, although well described as a metric influencing fishing performance (Millischer & Gasuel 2006, Powell et al. 2003, 2015), are not further investigated in this model.

When the pole is moved, a random start point near the pole is identified for the first tow. From this point, the boat dredges along an arcuate path around the pole until (1) the tow is completed, (2) the tow path extends beyond the reef, or (3) the handling time to cull oysters from the preceding tow is exceeded. The assumption is that no further oysters are caught during that time regardless of whether the dredge is deployed or not (see Powell et al. 2001, Banta et al. 2003). A new tow is then begun from the final point in the previous arc.

Dredge Tow Path and Catch

Each tow follows an arcuate path centered on the pole location. The starting point is defined by a direction from the pole. Each arc has a radius, defined as the distance from the pole to the dredge, that is chosen randomly from a range of values. To vary the directionality of the tow, 20% of the time the direction to the pole is reversed (changed by 180°), thereby putting the beginning of the arc on the other side of the pole. The fixed tow distance determines the length of the arc. These tow paths are of a specified length unless ended prematurely, as described earlier.

Catch is determined by the length of the tow path, the density of market-size oysters, and the inherent dredge efficiency. The number of oysters expected to be taken in a 2-min tow under average conditions is compared with a beginning 5-tow mean catch. If the average 5-tow harvest rate drops to a specified fraction of the average expected, then the pole is moved to a new location.

On-Deck Handling

Culling requires a specified time per sack culled. The onboard rate of sack production is determined either by the rate of catch in the dredge or by the specified limit to processing time on the boat. A tow is terminated early if the number of oysters caught reaches the maximum that can be handled on the deck in the time of a standard tow; but the total elapsed time is recorded as the total tow time which equates to the culling time required. In this way, the time on the bottom may be reduced to accommodate the culling time on the deck when the catch is of sufficient quantity.

A running time (in hours) for the simulation is recorded as though the dredging operation continues with no pauses. That is, such hiatuses as time spent searching for a new pole location are not accumulated. This running time can be converted to the number of days based on a judgment of the number of hours of dredging in a day or a regulated maximum catch per day. Economics as evaluated in this model are based on the cost of a standard fishing day. No attempt is made to adjust this cost for the variety of options of dredge number, crew onboard, vessel age, or steaming time to the reef, as the combinations of these metrics will vary widely.

Parameter Specifications

The following parameters are set for all simulations (see also Table 1). The number of market-size oysters per sack is set at 180, a value that is relatively arbitrary as the number per volume landed can vary considerably (e.g., Powell et al. 2005). The dredge width is set to 1.3 m, tow speed to 0.5 m sec^{-1} (Frey et al. 2018), and standard tow time is set to 2 min. Tow time and tow speed are variable in practice, but the influence of these specifications is minimized by the inclusion of on-deck culling time

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TABLE 1.

Values used in the simulations.

Fixed value	
Oysters per sack = 180	Tow duration = 2 min
Dredge width = 1.3 m	Tow speed = 0.5 m sec^{-1}
Daily boat cost (6 h fishing) = $248	–
Variable value	
On-deck processing = [1, 2, 5, 10, 15] sacks h^{-1}	Dredge efficiencies = [5, 10, 20, 40%]
Initial oyster density = [1, 5, 10, 25, 50] # m^{-2}	Oyster value = [$15, $25, $40] per sack
Arc radius range = [(10–30), (30–60), (60–100)] m	–

and the assumption that dredge retrieval and deployment time is short. For larger boats with two dredges, this is certainly true (Banta et al. 2003). The trigger to force a change in the pole location is set as a decrease in the rate of catch set to 50% of the initial rate for the first five tows.

The following parameters were varied in the simulations. On-deck processing capacity was set to 1, 2, 5, 10, or 15 sacks h^{-1} consistent with Powell et al. (2001) and Menzel and Hopkins (1952). The largest value applies to simulations where culling time has a limited effect on the rate of harvest, where, for example, oysters are culled rapidly by an automatic culling machine and then deck-loaded to be moved to a leased ground for later sale. Initial oyster density was set to 1, 5, 10, 25, or 50 market-size oysters m^{-2} which covers a range of densities often encountered on fished reefs (Powell et al. 2008, Mann et al. 2009, Southworth et al. 2010, Soniat et al. 2019) but substantively below carrying capacity estimates (e.g., Moore 1907, Powell et al. 1995, 2012). Higher sacking rates are feasible (Menzel & Hopkins 1952) as are higher oyster densities (Powell et al. 2008).

The radius of the curvature of the arc of the tow uses one of the following ranges: 10–30, 30–60, or 60–100 m. The arc radius is related to the boat turning rate required to travel in such a path; the heading change is inversely proportional to the arc radius (Fig. 1). As an example, a boat 10 m in length would show a continuous heading change of 57° and 9.5° to follow a path with a radius of 10 and 60 m, respectively. Observations are limited to Banta et al. (2003), in which the radius of the arc was constrained by the experimental protocol, and so offer only modest guidance. The inherent dredge efficiency was set to 5%, 10%, 20%, or 40%, a range of dredge efficiencies obtained by Morson et al. (2018) and Banta et al. (2003).

The economic calculation uses a day rate of $248 for a day of fishing, based on values for 2005 (Mykoniatis & Ready 2016) and corrected for inflation to 2019 dollars. Per-sack prices for oysters vary widely, particularly in the comparison of oysters shucked to supply oyster meats for breading and frying, for example, in comparison with those sold into the half-shell trade (Keithly & Diop 2001, Wirth & Minton 2004). Values of $15, $25, and $40 $sack^{-1}$ were used to cover a broad range of potential outcomes.

RESULTS

Approach

Three diagnostics are used to compare simulations: (1) the fraction of the initial oyster stock remaining when harvest becomes unprofitable, (2) the number of days dredging until harvest becomes unprofitable, and (3) the time when the 4-day average catch rate falls to less than or equal to 95% of the average catch rate in the preceding 4 days. The value of the first two of these diagnostics varies depending on the assumed price per sack. Each of these diagnostics are presented for different choices of model parameters.

Radius of Arc

Vessels typically tow in an arc, the size of which has little impact on three important metrics: (1) the number of days that a

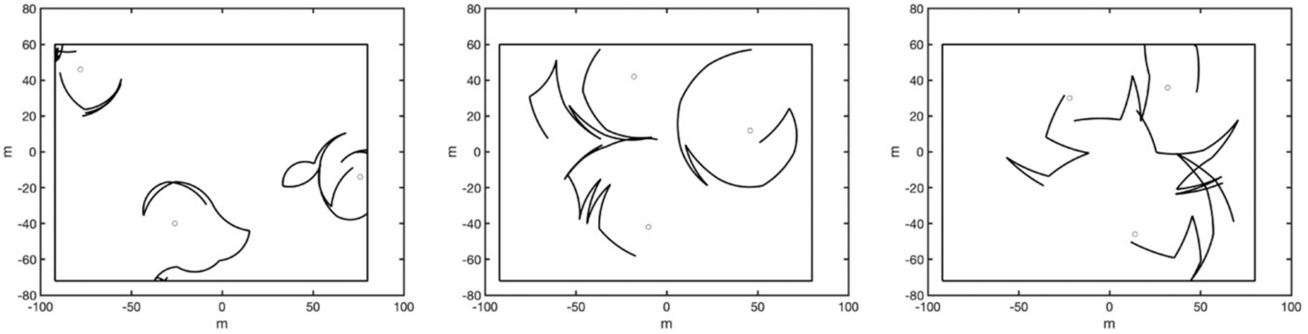

Figure 1. Vessel trajectories (in black) for the three cases defined by arc radii (in m). Plots show the first 30 tows, 10 each around three pole locations. Left, a vessel fishing in tight arcs (10–30 m from the pole). Middle, a vessel fishing in a gentler arc (30–60 m from the pole). Right, a vessel fishing in a much straighter but still arcuate trajectory (60–90 m from the pole).

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region can be profitably exploited, (2) the amount of stock remaining when profitability ceases, and (3) the number of days before an observable decline in catch (Table 2). In reality, the radius of the arc may affect dredge efficiency. In the simulations considered here that variation is divorced from variation in tow arc, as information that is available suggests that the degree of arc curvature has little effect on dredge efficiency (Powell et al. 2007).

Oyster Density and Culling Capacity

Oyster density, on-deck processing capacity, and dredge efficiency collectively generate a complex control over profitability and degree of exploitation. Figure 2 presents the fraction of stock remaining assuming that ex-vessel value per sack was \$15 or \$40. Over a large range of culling capacities and oyster densities, 40% or more of the stock could be removed profitably, with the higher ex-vessel value permitting a substantially higher removal. Culling capacity had limited impact at low oyster density except at the lowest culling capacities. Oyster density had limited impact at low culling capacities.

The number of profitable fishing days increased substantially at a higher ex-vessel value. Fewest profitable days occurred at culling capacities of 2–5 sacks h^{-1} (Fig. 3). The number of profitable days increased at higher culling capacities as more oysters were removed per day to offset declining stock densities and at lower culling capacities as stock density remained higher for a longer period of time.

In most simulations, a relatively constant catch rate occurs over an initial number of days, the time span of which is controlled by the relationship between on-deck culling capacity and stock density. Eventually, the stock density declines sufficiently that the efficiency of the dredge imposes a limit on the catch rate. At this point, the rate of catch begins to decline noticeably. For these simulations, a decline in the catch rate occurred after 50%–70% of the stock had been removed over a wide range of oyster densities and culling capacities, with the decline occurring to the lowest stock fractions removed (highest stock fractions remaining) with oyster densities of 5–10 m^{-2} and culling capacities of 5–10 sacks h^{-1} (Fig. 4). The number of fishing days before a stock decline occurred rose with increasing stock density and presented a complex relationship with culling capacity with higher numbers of fishing days above and below approximately 2 sacks h^{-1}.

Oyster Density and Dredge Efficiency

Figure 5 presents the fraction of initial stock remaining for ex-vessel sack values of \$15 or \$40 over a range of oyster densities and dredge efficiencies. Dredge efficiency has little effect on the amount of stock remaining when fishing becomes unprofitable over a range of oyster densities commonly encountered. The degree of depletion is primarily determined by ex-vessel value, approximately 70% at high ex-vessel value and approximately 40% at low ex-vessel value, over a range of typical oyster densities. At oyster densities above 5 m^{-2}, however, a larger fraction of stock remained at low dredge efficiencies and the effect was particularly noticeable when ex-vessel value was high.

Dredge efficiency did not affect the number of profitable fishing days regardless of ex-vessel value. Variation was solely a function of oyster density (Fig. 6). Dredge efficiency exerted a complex effect on the amount of stock remaining when the catch rate noticeably began to decline (Fig. 7). At high oyster densities, dredge efficiency was relatively inconsequential unless efficiency was very low. The effect of dredge efficiency nearly disappeared at very low oyster densities. At intermediate densities, the density at which the catch noticeably declined varied from 30% to 60% of the original density, but fell to less than or equal to 20% at higher and lower oyster densities. The number

TABLE 2.

Metrics for a series of simulations in which dredge efficiency, path radius, on-deck processing capacity, and oyster density were varied.

Dredge efficiency	Radius of arc	Deck culling capacity	Oyster density	Last profitable day: \$15 $sack^{-1}$	Last profitable day: \$25 $sack^{-1}$	Last profitable day: \$40 $sack^{-1}$	Fraction remaining: last profitable day: \$15 $sack^{-1}$	Fraction remaining: last profitable day: \$25 $sack^{-1}$	Fraction remaining: last profitable day: \$40 $sack^{-1}$	Decline day
0.1	10	10	5	12	20	31	0.692	0.573	0.467	0
0.1	60	10	5	12	23	32	0.706	0.552	0.472	0
0.1	30	10	5	11	20	32	0.722	0.587	0.476	0
0.4	10	2	10	0	96	103	1.000	0.352	0.319	94
0.4	30	2	10	0	96	103	1.000	0.353	0.322	94
0.4	60	2	10	0	95	103	1.000	0.359	0.321	92
0.4	10	10	5	12	16	20	0.430	0.369	0.333	5
0.4	30	10	5	13	16	20	0.421	0.375	0.341	5
0.4	60	10	5	13	17	20	0.425	0.369	0.342	5
0.4	10	10	10	25	28	30	0.352	0.331	0.322	14
0.4	30	10	10	25	29	31	0.358	0.331	0.322	12
0.4	60	10	10	25	27	31	0.356	0.341	0.322	11
0.4	10	10	50	109	113	117	0.306	0.300	0.297	92
0.4	30	10	50	109	114	117	0.306	0.299	0.297	93
0.4	60	10	50	106	112	115	0.310	0.300	0.297	94

Diagnostics are the last profitable day, the fraction of stock remaining on that day, and the day when the 4-day mean catch rate declines greater than or equal to 5% below the previous 4 days.

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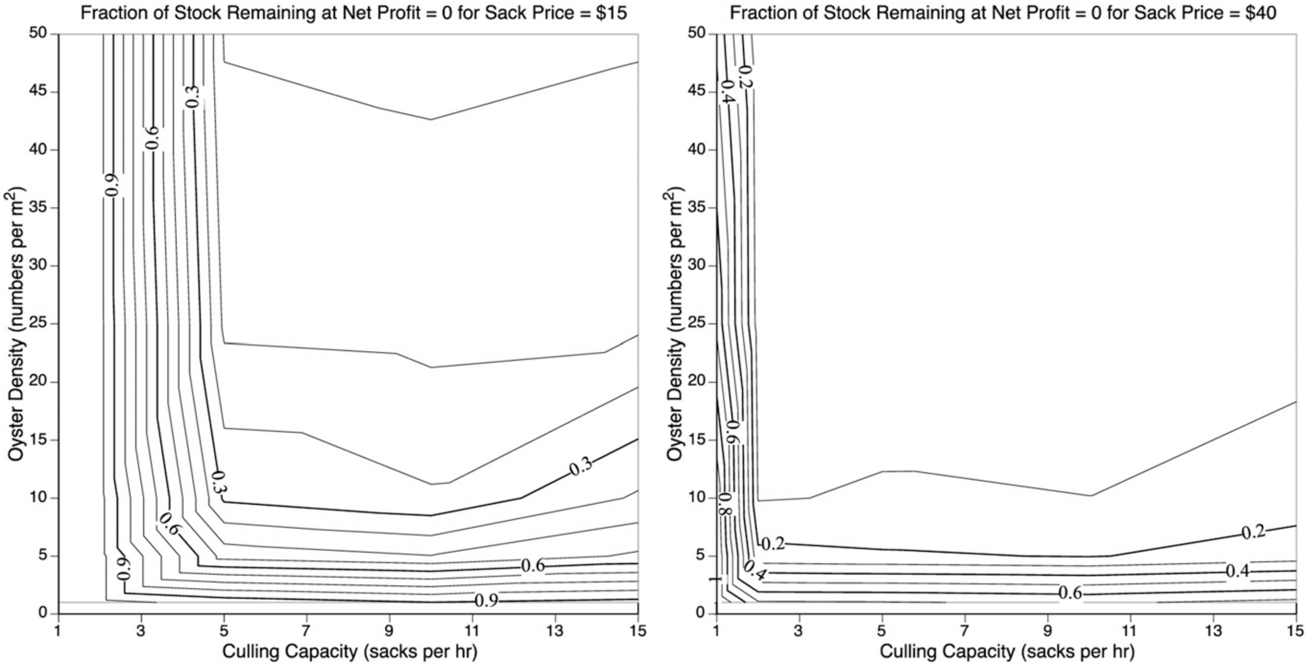

Figure 2. Fraction of initial stock remaining when fishing becomes unprofitable at a range of culling capacities and oyster densities, given ex-vessel values of $15 and $40 sack^{-1}. Simulation parameters are given in Table 1.

of days fishing before a noticeable drop in the catch rate was relatively little influenced by dredge efficiency (Fig. 7).

Dredge Efficiency and Culling Capacity

Dredge efficiency had limited effect on the stock remaining when profitable trips ceased at low culling capacity (Fig. 8). At higher culling capacity, dredge efficiency was the primary determinant. The time required was relatively unaffected by dredge efficiency, regardless of culling capacity (Fig. 9). The number of fishing days required to see a distinct decline in the catch rate was relatively unaffected by dredge efficiency, regardless of culling capacity (Fig. 10). The fraction of stock remaining ranged near 30% over a wide range of dredge efficiencies and culling capacities, only dropping below that at high dredge efficiencies and low culling capacities or *vice versa*.

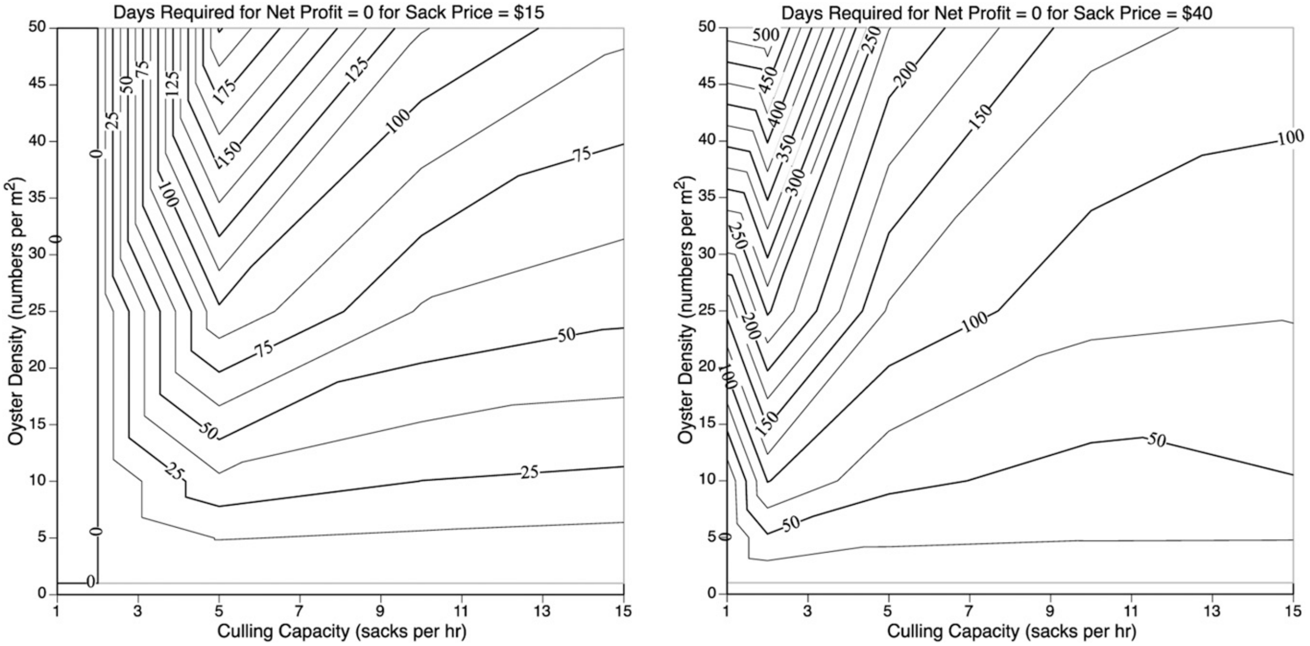

Figure 3. Number of fishing days before fishing becomes unprofitable as a consequence of varying oyster density and culling capacity, given ex-vessel values of $15 and $40 sack^{-1}. See Table 1 for simulation parameters.

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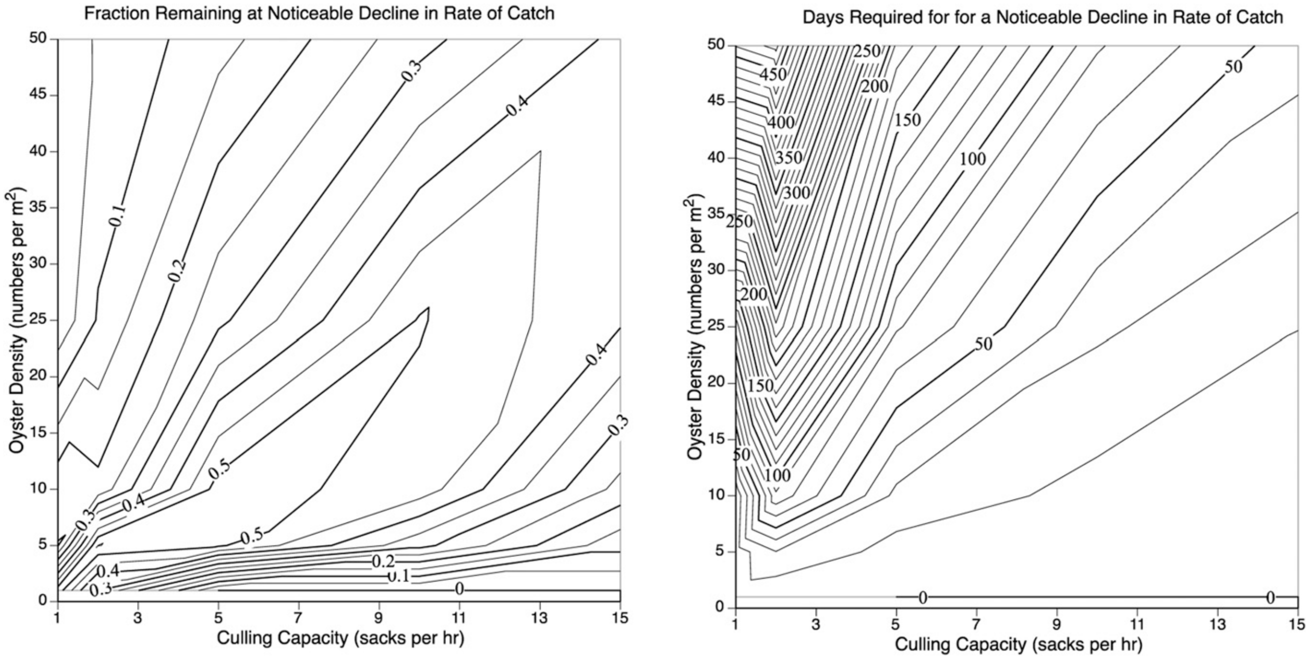

Figure 4. Number of fishing days before a noticeable decline in the catch rate (defined as a 5% reduction in the 4-day mean catch rate from the previous 4 days) and the fraction of initial stock remaining at that time as a consequence of varying oyster density and culling capacity. See Table 1 for simulation parameters.

Status at F_{msy} Catch

Powell et al. (2018) estimated sustainable fishing mortality at maximum sustainable yield (F_{msy}) as 0.06 y^{-1}. Dredge efficiency exerted a limited effect on the number of days fishing allowed in order to catch approximately 6% of the stock (Fig. 11). Lower culling capacity resulted in more days fishing, as did higher oyster densities.

DISCUSSION

Metrics Controlling Vessel Performance

Simulations were run under the assumption that factors controlling the economics of an oyster fishing trip include the rate at which oysters are brought onto the deck and the rate at which oysters could be culled for sacking. With respect to the

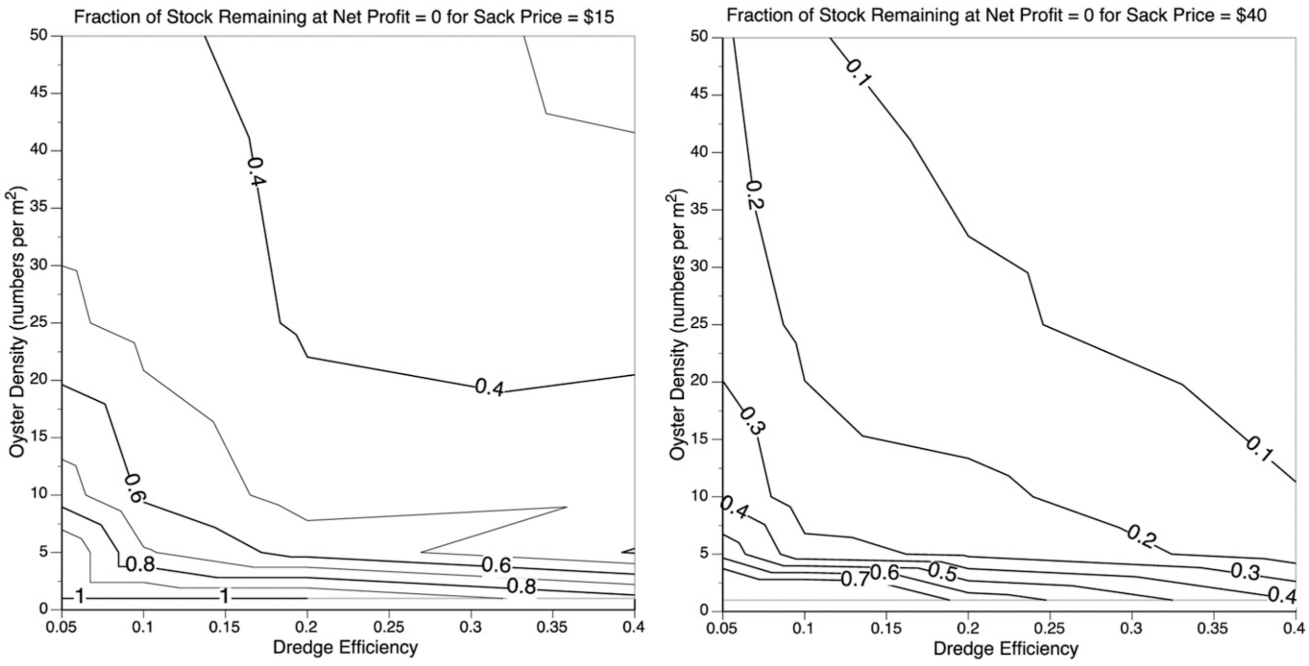

Figure 5. Effect of oyster density and dredge efficiency on the fraction of the initial stock remaining when fishing becomes unprofitable, given ex-vessel values of \$15 and \$40 sack^{-1}. See Table 1 for simulation parameters.

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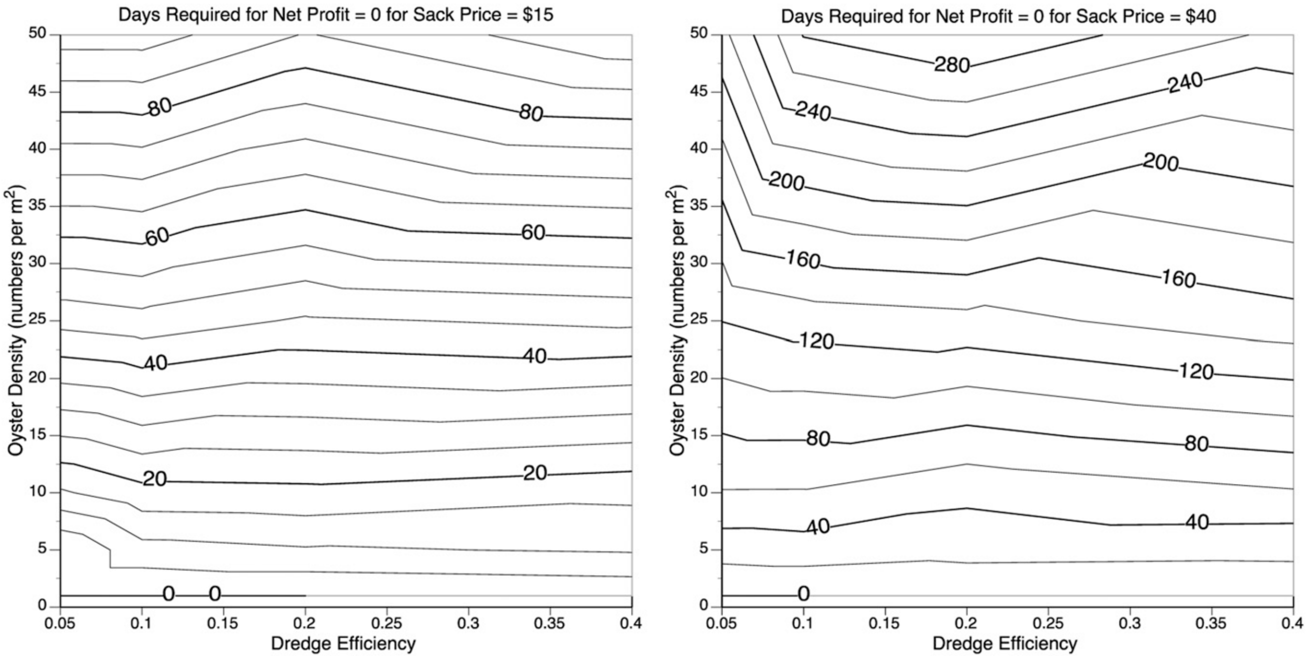

Figure 6. Number of fishing days before fishing becomes unprofitable as a consequence of varying oyster density and dredge efficiency, given ex-vessel values of $15 and $40 sack^{-1}. See Table 1 for simulation parameters.

rate of capture, the assumption was made that this depended on the density of oysters on the bottom, the efficiency of the dredge, and the behavior of the vessel. That behavior was defined by the culling capacity on the deck and the radius of the arc of the tow, although discriminating the arc radius from dredge efficiency is difficult as the two effects are commingled. Tow speed was not varied, as oyster boats normally tow at a slow speed so that the dredge teeth can effectively bite into the bottom. Higher speed (Frey et al. 2018) would necessarily be counterweighed by culling capacity. As oyster boats routinely tow in an arcuate fashion, all tows were arcs, but the degree of the arc was varied.

Navigation was used in the standard way whereby a fishing location is identified by test tows or by pole, a marker, buoy or pole is placed in water, and the dredge is towed in an arc around that the marker until a reduction in catch results in a search for a new fishing location. Frey et al. (2018) provide estimates of the

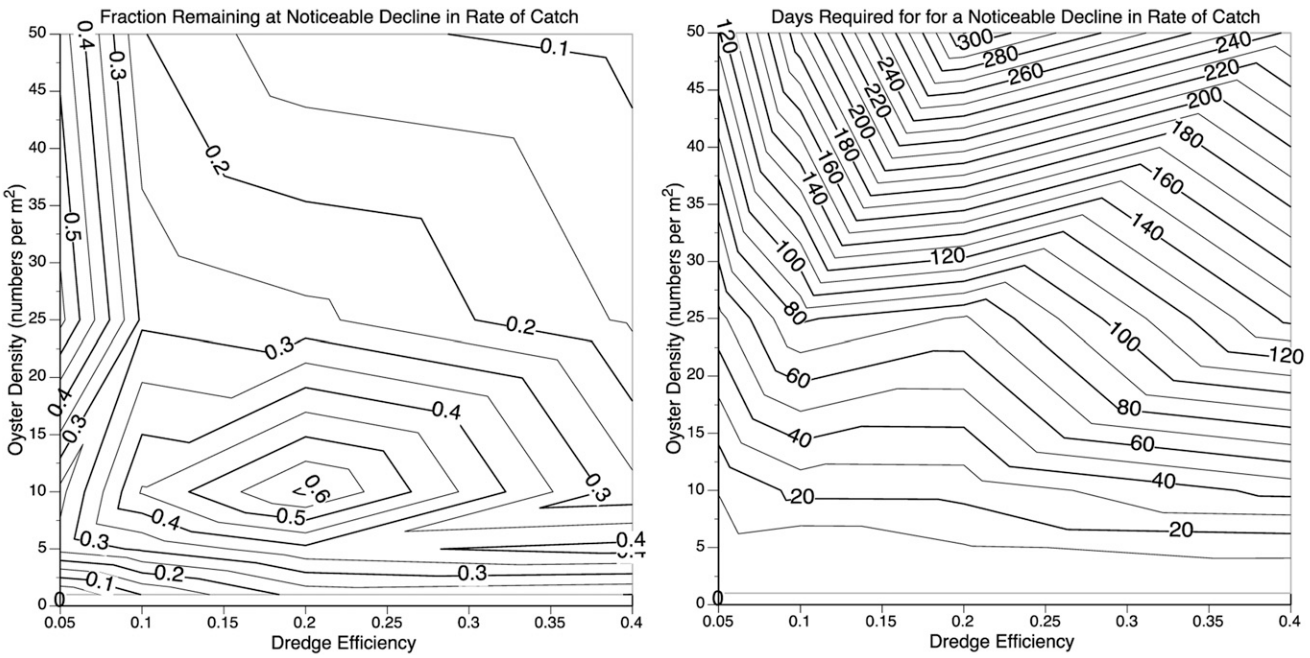

Figure 7. Number of fishing days before a noticeable decline in the catch rate occurred and the fraction of initial stock remaining at that time as a consequence of varying oyster density and dredge efficiency. See Figure 4 for addition explanation. See Table 1 for simulation parameters.

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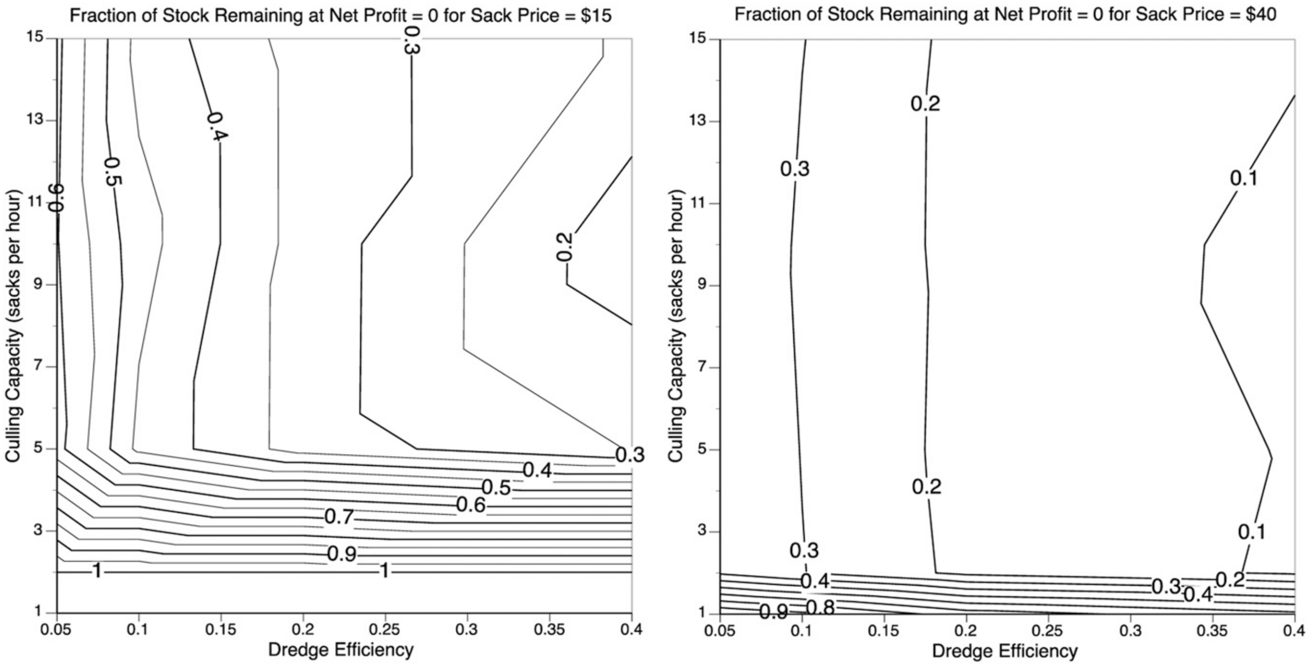

Figure 8. Fraction of initial stock remaining when fishing becomes unprofitable, given ex-vessel values of $15 and $40 sack^{-1} as a consequence of varying oyster density and dredge efficiency. See Table 1 for simulation parameters.

time spent poling; a 6-h fishing day was assumed, yielding a dock-to-dock elapsed time of 7–8 h. Shorter fishing times, due, for example, to temperature restrictions in the summer, were not investigated but would have substantively influenced the economics.

Four additional constraints were imposed. A sack was defined to contain 180 marketable oysters. That value certainly varies widely in practice (Hopkins 1950, Campbell et al. 1992, Powell et al. 2005, zu Ermgassen et al. 2012). The vessel was assumed to tow a single dredge at a time, although two-dredge boats are common (Banta et al. 2003). The cost of one-day fishing was set to $248, based on Mykoniatis and Ready (2016), but this value surely is highly variable depending on vessel size, crew complement, remoteness of fishing site, fuel cost, etc. In

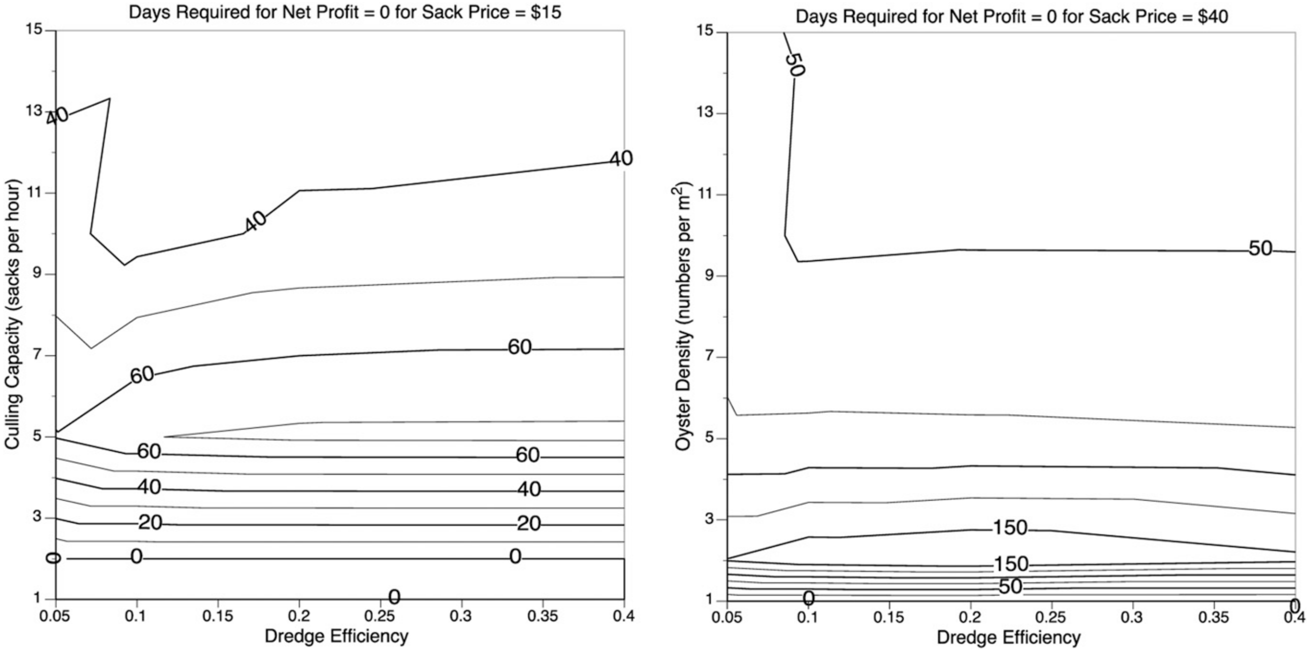

Figure 9. Number of fishing days before fishing becomes unprofitable as a consequence of varying culling capacity and dredge efficiency, given ex-vessel values of $15 and $40 sack^{-1}. See Table 1 for simulation parameters.

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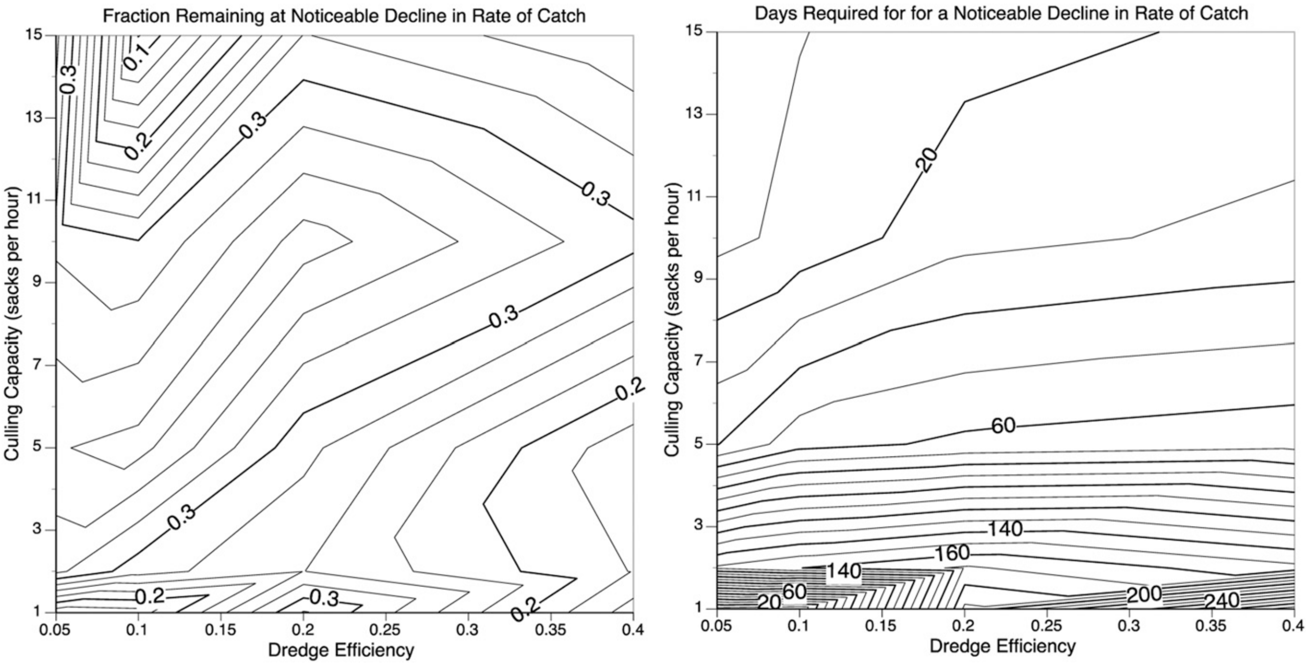

Figure 10. Number of fishing days before a noticeable decline in the catch rate occurred and the fraction of initial stock remaining at that time as a consequence of varying culling capacity and dredge efficiency. See Figure 4 for additional explanation. See Table 1 for simulation parameters.

addition, the sack price is variable: a range of $15 to $40 was used, but values often fall outside of this range (Lipton 2008, Kasperski & Wieland 2010).

Documentation of fishing activity adequate for verification is limited. Powell et al. (2001) and Banta et al. (2003) recorded the inefficiency imposed by on-deck processing which resulted in the effectiveness of the dredge being inconsequential, in agreement with results provided here. Powell et al. (2007) observed little influence of the radius of the tow arc on dredge efficiency. Perhaps, the only detailed and pertinent field experiment is reported by Menzel and Hopkins (1952), who emphasize a drop in catch observed only after many days fishing and that profitability limits are reached when a substantial oyster resource still remains. Menzel and Hopkins (1952) opine that about 60% (values varied from 41% to 76%) of the resource can be profitably removed, in agreement with simulations presented here.

The radius of the arc of the tow introduced minor variations in the outcome of simulations, consistent with Powell et al. (2007). As tow paths cross each other frequently and variation in this factor is known to influence the outcome of stock depletion due to fishing (Poussard 2020), and as oyster boats do not use sophisticated towing procedures to limit tow overlap, the radius of arc was inconsequential in determining the frequency and intensity of tow overlap and, as a consequence, exerted only minor influence on vessel performance.

The inherent efficiency of oyster dredges has been evaluated in a number of studies (e.g., Chai et al. 1992, Powell et al. 2002,

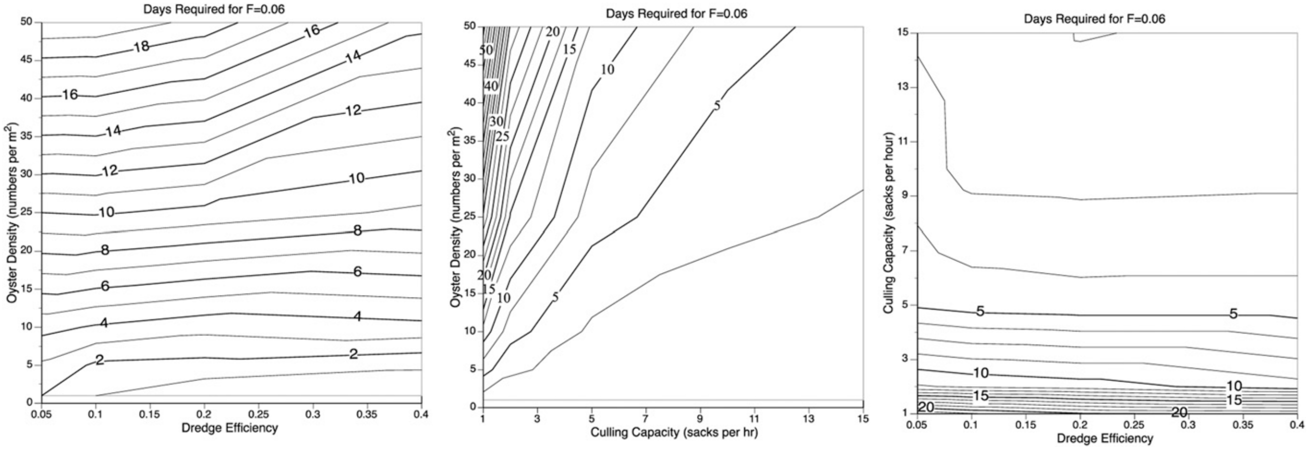

Figure 11. Days of fishing allowed to land catch consistent with an assumed $F_{msy} = 0.06\ y^{-1}$ as a function of oyster density, dredge efficiency, and culling capacity. See Table 1 for simulation parameters.

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2007, Mann et al. 2004, Morson et al. 2018) and has proven to be highly variable. Under fishing conditions, dredge efficiency tends to decrease as the dredge fills and be modified by bottom conditions that change as fishing continues (Powell et al. 2001, Powell & Ashton-Alcox 2004, 2013), increasing variability. One inherently expects higher dredge efficiency to produce increased vessel performance. In fact, dredge efficiency exerted very little influence on vessel performance except when both oyster density and culling capacity were high. Over a wide range of oyster densities and culling capacities, the efficiency of the dredge exerted practically no effect.

Why dredge efficiency exerts little influence on the fishing process is found in the frequency of tow overlap. Depletion decouples the capture rate from the inherent dredge efficiency as towing continues. As towing progresses, the tow path increasingly intersects previous tow paths and the number of times a particular spot is hit by the dredge inexorably exerts control on the capture rate, drowning out any role of dredge efficiency. Poussard (2020) provides a useful theoretical example. Note, in simulations presented here, Figure 12 being an example, that the trajectories of catch with culling capacity and oyster density fixed to 5 sacks h^{-1} and 10 oysters m^{-2}, respectively, are nearly identical over a range of dredge efficiencies, in comparison with the trajectories for a dredge efficiency of 0.2 and an oyster density of 10 m^{-2} in which culling capacity was varied.

In comparison, vessel performance is strongly controlled by oyster density and culling capacity. These two conspire to create a catch rate that is relatively stable for a period of time and then declines (Fig. 12). The time delay before catch begins to decline is influenced by oyster density and culling capacity in a relatively complex way as exemplified in Figure 4 in which increasing culling capacity reduces the time spent fishing before a noticeable decline in catch occurs, and this is balanced by an increase in oyster density.

Effect of Vessel Performance Metrics on Trip Economics and Degree of Depletion

Not surprisingly, the degree of stock depletion culminating in unprofitable trips varies widely as a function of culling capacity and oyster density. Over a very large range of these parameter values, profitability ceases when 70%–80% of the initial stock has been landed (Fig. 2). These high values, however, are based on the unrealistic assumption that even \$1 of profit incentivizes continued fishing. This end point is used for these simulations to generate a common basis for comparison. In actuality, fishing likely would cease at much lower levels of stock depletion. Figure 13 shows as an example a case where 30 sacks day^{-1} is required to incentivize fishing at an ex-vessel value of \$15 $sack^{-1}$. Thirty sacks per day is a landing limit set by Texas at this writing. In this case, save under exceptional conditions, the incentive to fish would cease after removal of no more than 40% of the total stock, given the specified cost per day of fishing.

Not surprisingly, the degree of depletion that is profitable rises with a higher ex-vessel value, but the number of days fished declines. Over a wide range of combinations of oyster density and culling capacity, a noticeable decline in catch occurs when 50%–70% of the stock has been removed. These values agree reasonably well with field observations of Menzel and Hopkins (1952).

Simulations show that the oysterman will not observe a substantive drop in catch until the degree of depletion of the resource is profound. Examples are shown in Figure 12. This is dominantly a function of the time required to cull oysters on the deck. Dredge efficiency is relatively inconsequential, as is the mode of dredging as exemplified by the radius of the tow arc. Simulations show that the trip will remain profitable for a substantive time after the catch begins to decline. A 6-h day and a culling capacity of 5 sacks h^{-1} produce 30 sacks. To put this in perspective, the State of Texas at this writing limits landings in Galveston Bay to 30 sacks day^{-1}. Under most of the

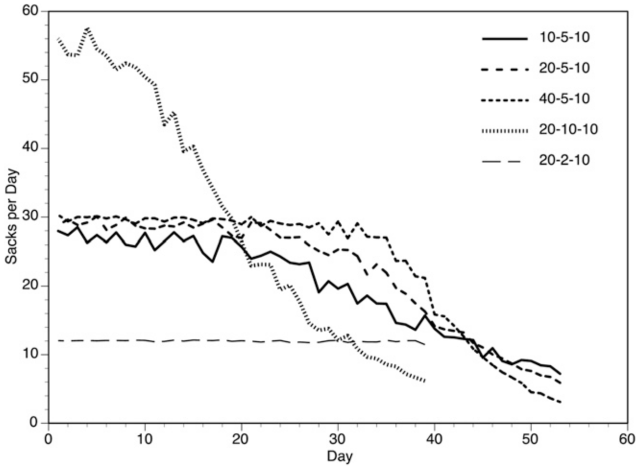

Figure 12. Trajectories of catch in which culling capacity and dredge efficiency were varied. The three-digit legend is dredge efficiency (%)-culling capacity (sacks h^{-1})-oyster density (oysters m^{-2}).

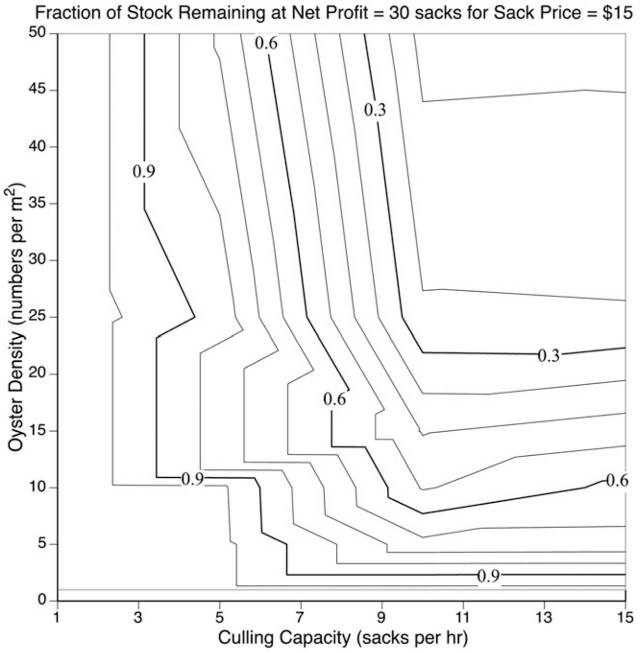

Figure 13. Fraction of initial stock remaining when fishing becomes unprofitable at a range of culling capacities and oyster densities, given an ex-vessel value of \$15 per sack and under the assumption that a 30-sack minimum was required for a trip to be deemed profitable. Simulation parameters are given in Table 1.

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conditions of the simulations depicted in Figure 12, the vessel could operate 30–40 days before a noticeable decline occurred and, perhaps, another 10–30 days before profitability was compromised, depending on the ex-vessel value of a sack.

Powell et al. (2018) suggested that a fishing mortality rate exceeding 0.06 y^{-1} is unsustainable, given the pervasive influence of Dermo disease raising the natural mortality rate above pre-disease levels. A reduction in stock density to this extent would occur in 5 or so days under the conditions shown in Figure 11. That is, under a sustainable fishing criterion, the oysterman would never observe a decline in the rate of catch under almost any combination of culling capacity, oyster density, and dredge efficiency (Fig. 10).

Final Considerations

D'Anna (2016) offers a view into the challenge of reconciling perception and reality in sustainably managing oyster fisheries. Routine overfishing, which has resulted in the degradation of oyster reefs throughout much of the range of the eastern oyster (Rothschild et al. 1994, Beck et al. 2011, zu Ermgassen et al. 2012, Pine et al. 2015, Soniat et al. 2019), results from the nexus of a number of independent factors. The first is the fact that oyster shell degrades with a half-life of about 4–5 y (Powell et al. 2006, Pace et al. 2020). As a consequence, a significant fraction of the living oysters must die naturally to compensate for shell loss. Second, Dermo disease accounts for a large fraction of surplus production, thereby limiting the sustainable fishing rate (Powell et al. 2018). Third, the oyster fishery does not perceive a decline in the stock under sustainable conditions, as the on-deck processing capacity remains relatively stable until the stock declines well below sustainable levels. The consequence of setting fishing regulations such that a decline in catch is perceived is to assure routine and substantive overfishing. The perception that a decline in the rate of catch should be observed under standard effort-based regulatory controls is a principal challenge that must be overcome if sustainability is to become normative in the U.S. oyster fishery.

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