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Biofouling in Marine Molluscan Shellfish Aquaculture: A Survey Assessing the Business and Economic Implications of Mitigation

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Abstract

The culture of oysters, clams, scallops, and other molluscs is collectively one of the fastest growing sectors of the domestic aquaculture industry. An inherent issue with shellfish culture methods, particularly for off-bottom culture (i.e., floating trays, racks, long lines, strings, rafts), is biofouling. Controlling and mitigating biofouling can result in significant costs for commercial shellfish culture operations. A survey of existing commercial shellfish culture operations was conducted among growers in seven US regions. A total of 1375 surveys were distributed. An overall response rate of 37% was achieved. The survey solicited information on business descriptors, perceptions of biofouling as a problematic issue, and costs associated with control. Respondents indicated that efforts to control biofouling accounted for an average of 14.7% of total annual operating costs. Survey findings suggest that the total costs associated with biofouling control by shellfish growers in the regions studied exceed $21 million. Over 40% of respondents indicated that biofouling affected the marketability of their product. The survey findings reveal significant variation in responses by region.

Marine aquaculture has become an important component of the US domestic aquaculture industry, which reported farm-gate sales of $1.1 billion in 2005 (US Department of Agriculture 2006). Of this total, $203 million (19%) was associated with molluscan shellfish culture. The culture of oysters, clams, scallops, and other molluscs is collectively one of the fastest growing sectors of the industry, with aggregate sales increasing by almost 130% from 1998 to 2005 (US Department of Agriculture 2006). Of the total number of molluscan shellfish growers, approximately 80% utilize bottom culture techniques, while the remaining growers utilize off-bottom methods (US Department of Agriculture 2006). An inherent issue with both types of culture methods, but particularly for off-bottom culture (i.e., floating trays, racks, long lines, strings, rafts), is biofouling. Fouling organisms are those that grow in unwanted locations, such as on aquaculture gear, as well as on the cultured animals themselves, and thereby impede the efficient growth of the culture organism and maintenance of the culture system.

Impacts of biofouling on molluscan shellfish and aquaculture can be extreme and sometimes devastating (Watson et al. 2009). These impacts vary with geographic location, shellfish species, habitat, and method of culture. Ascidians, or sea squirts, are among the most common and devastating biofoulers to shellfish aquaculture operations (Eno et al. 1997; Campbell 2002;

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NIMPIS 2002a, 2002b; Ross et al. 2002, 2004), although both native and non-native organisms such as barnacles, hydroids, other bivalve molluscs, and macroalgae are also common.

Biofouling organisms compete for the same spatial, hard substrate and planktonic food resources as oysters and mussels (Duggan 1973; Leighton 1978, 1998; Côté et al. 1993; Wilson 1994; Lodeiros and Himmelman 1996, 2000; Lu and Blake 1997), and they also can attach and grow on the shells of these bivalves. This means that their abundance can be enhanced by increased shellfish abundance and their ability to grow on shells can increase their capacity to compete for food and to overgrow the mussels or oysters. In addition, water exchange (Claereboudt et al. 1994) and oxygen levels (Huguenin and Huguenin 1982; Enright 1993; Lu and Blake 1997; Cronin et al. 1999; Mazouni et al. 2001) can be affected, causing mortality or reduced growth (Boyd 1982; Laired and Needham 1988). Fouling restricts shell opening and closing for respiration and feeding (Minchin and Duggan 1989; Lu and Blake 1997; Lodeiros and Himmelman 2000) and increases shellfish vulnerability to predators. The use of cages, mesh bags, trays, ropes, racks, rafts, and other gear in aquaculture provides additional surfaces for the fouling species to grow on, increasing their local abundances and further expanding their ability to compete with the shellfish. The use of various methods of off-bottom aquaculture that provide refuge to shellfish from predators and sedimentation also extends the same benefits to the fouling species, increasing their abundance. All of these aspects of fouling of the shellfish and gear can result in significant added labor costs associated with gear maintenance, cleaning of harvested shellfish, and can seriously affect the value of the end product.

Controlling and mitigating biofouling can result in significant costs for commercial aquaculture operations. Though no formal, comprehensive estimates exist for the US aquaculture industry, the Collective Research on Aquaculture Biofouling (C.R.A.B.) (2004) suggests that the costs associated with efforts to control biofouling represent between 5 and 10% of the total European Union aquaculture industry value. Studies by Lesser et al. (1992), Lodeiros and Himmelman (1996), Rickard and Wallace (1997), and Ross et al. (2002) have clearly demonstrated the degree to which biofouling organisms can be problematic to molluscan shellfish growers in the USA.

Many millions of dollars have been spent on research and trials to eradicate biofouling (Shumway et al. 1988; Cigarria et al. 1998; MacNair and Smith 2000; Carver et al. 2003; LeBlanc et al. 2003, 2007; Coutts and Forrest 2007; Forest et al. 2007; Watson et al. 2009). The fact that biofouling can have profound and extreme impacts on shellfish aquaculture is indisputable, and shellfish growers are in agreement that biofouling poses a large financial burden to their industry. For example, estimates of the cost of biofouling to the shellfish aquaculture industry have been estimated at 20% of the final market price for the oyster, *Ostrea edulis* (Enright 1993); 30% for the scallop, *Placopecten magellanicus* (Claereboudt et al. 1994); and 5–30% of overall costs per annum for oysters (C.R.A.B. 2004). Thus, the magnitude of the impacts remains based largely on anecdotal information, because costs to the industry related to biofouling have not been assessed in a rigorous and systematic manner.

As part of a larger study on the control of aquatic invasive species in marine aquaculture, a survey was developed to assess specific impacts of biofouling on production and marketing, and to determine the economic implications associated with fouling on shellfish aquaculture. A mail-out survey instrument was distributed to a select group of individual molluscan shellfish aquaculturists in the coastal USA to solicit information regarding the impacts of biofouling. The questionnaire requested information regarding the types of biofouling organisms present, methods currently utilized to control biofouling, labor investment in the current control methods, estimates of impacts on production because of biofouling (i.e., changes in shellfish growth rate, mortality, and other factors), and estimates of the financial costs associated with biofouling and current control methods. The primary goals of this survey were to: (a) assess the degree to which biofouling is currently a problem with shellfish growers; (b) determine the manner in which biofouling affects the shellfish culture business operation; and (c) estimate the economic costs associated with current biofouling control methods. Results of that survey are presented here in an effort to allow insight into the potential economic benefits that might accrue to US molluscan shellfish growers if successful biofouling control methods are developed.

Materials and Methods

A survey of existing commercial shellfish growers was conducted. The survey focused on those growers who utilized some form of gear in which the molluscan shellfish culture process occurred. As assessing the problematic nature of biofouling on culture gear was the primary objective of the study, culturists who utilized managed reefs (e.g., private oyster reefs in the Gulf coast region) were excluded. A mail survey was determined to be an appropriate and cost-effective method to survey existing shellfish growers. The survey made use of the modified Dillman procedure (Dillman 1978) as described below, as this method helps ensure a maximum return rate.

Lists of commercial shellfish growers were obtained from industry association membership lists, industry contacts, university extension contacts, and state agencies in seven regions or states of the USA (from now on referred to as "regions"). These regions included the West Coast (Washington, Oregon, and California), Northeast coast (Maine through Maryland), Virginia, North Carolina, South Carolina, Georgia, and Florida. These regions were deemed to be the major shellfish culture regions utilizing submerged or floating gear. The lists obtained from each region were deemed to be the respective region's population of commercial growers. Thus, all growers on the respective regional lists were sent a questionnaire. The survey questionnaires were initially field tested with a small group of willing industry members, then distributed during Spring and Summer of 2006. An initial mailing of questionnaires was sent to individuals on the distribution list of each region, followed a month later by a reminder letter accompanied by another questionnaire.

The questionnaires solicited several types of information. First, information describing the culture operation was requested, such as the number of years of shellfish culture experience, species cultured, and production systems utilized. Second, the degree and manner in which biofouling was deemed a problem was solicited; for example, the respondent was asked to assess how problematic biofouling was to the operation, to describe the extent biofouling had become more or less a problem, and to indicate the specific production issues biofouling created. Respondents were asked to describe the methods currently being used to control biofouling. Next, respondents were asked to characterize the economic costs associated with biofouling. Finally, respondents were asked to describe how biofouling affected the marketability of their product.

Results

A total of 1375 surveys were distributed. Of these, 510 completed surveys were returned, for an overall response rate of 37%. The response rate varied across survey regions (Table 1). For example, the North Carolina, South Carolina, and Georgia components of the survey exhibited response rates of 42, 39, and 55%, respectively; however, the combined total of completed surveys for these three regions only comprised 9% of the total number of completed surveys. The return rates for the West Coast, Northeast Coast, Florida, and Virginia, which were the larger components of the total number of survey returns, were 40, 41, 31, and 33%, respectively. The relatively high response rates suggest a strong interest in the topic amongst survey questionnaire recipients.

Business Descriptors

Information concerning total years in the shellfish culture business, species cultured, and primary culture methods were solicited by the survey (Table 2). This information provides some explanatory power regarding the

TABLE 1. *Sample size and response rate, by region.*

State/Region	# of surveys distributed	# of surveys completed and returned[1]	Regional response rate (%)
West Coast	390	156	40
Alaska		14	
California		12	
Washington		103	
Oregon		5	
Northeast Coast	341	140	41
Connecticut		14	
Massachusetts		67	
Maine		27	
New York		6	
Rhode Island		6	
Virginia	126	41	33
North Carolina	74	31	42
South Carolina	23	9	39
Georgia	11	6	55
Florida	410	127	31
Total	1375	510	37

[1]The values for each state represent the total number of returned surveys where state address of the respondent was provided. Thus, the total number of returns for the West Coast and Northeast Coast region do not add up to the sum across individual states because of some respondents not providing their state address.

linkage between these key business descriptors and the incidence and costs associated with biofouling.

Years in Shellfish Culture. The average number of years that respondents were in shellfish culture was the greatest for the West Coast region (22.2 years). Though not shown in Table 2, the years of experience for West Coast growers exhibited the following percentage distribution among the 133 respondents: 0–10 years (38.3%), 11–20 years (2.3%), 21–30 years (21.1%), and over 30 years (17.3%). (The "years of experience" distribution among respondents, in an ordinal sense, was similar for the other states and regions.) Respondents from the northeast region and South Carolina averaged 15 years experience. Respondents from Virginia, North Carolina, Georgia, and Florida averaged 14.1, 13.6, 8.2, and 7.9 years of experience.

Species Cultured. With minor exceptions, eastern oysters, *Crassostrea virginica*, and hard clams/northern quahogs, *Mercenaria mercenaria*, dominated the list of molluscan shellfish species cultured by growers in the region from Virginia to Florida. For the northeast region, eastern oysters were the predominant species cultured (87.9%), but an assortment of other species was also noted, such as flat oysters, *O. edulis;* mussels, *Mytilus edulis;* and scallops, *Argopecten irradians*. For the West Coast respondents, the list of species cultured was much more diverse. Approximately 76% of the respondents cultured Pacific oysters, *Crassostrea gigas*, while 67.7% cultured eastern oysters. Other oyster species cultured included flat; Kumamoto, *Crassostrea sikamea;* and Olympia, *Ostrea lurida*. West Coast growers also produced manila clams, *Venerupis philippinarum,* (34.6%); mussels (16.5%); geoducks (*Panopea abrupta*), (15%); hard clams (10.5%); and scallops (1.6%).

Culture Methods. The mix and relative importance of culture methods varied across the regions. This was due to the species being cultured, depth of water, degree of exposure to high-energy tides and waves, potential for ice-ups, use conflicts, and a host of other determining factors, including the potential for fouling. With few exceptions, the mix of culture methods employed were the same on both the West and East Coast regions, but the relative importance of the various methods was different. For example, planting seed directly on the bottom and the use of suspended lines were the most frequently selected culture methods for the West Coast, while the use of bottom cages was most frequently selected by the Northeast coast respondents. As expected, the predominant use of a specific culture method varied across the southeastern states, with bottom planting, the use of bottom cages, and suspended bags/cages/lines being methods in common among all the states. For Florida, many of the 48.2% of the respondents that selected "other" provided a description of soft bags on the bottom. The use of "other mesh" in the

TABLE 2. *Business descriptors for survey respondents, by region.*

Descriptor	West Coast	Northeast Coast	Virginia	North Carolina	South Carolina	Georgia	Florida
Average years, shellfish culture[1]	22.2	15.0	14.1	13.6	15.0	8.2	7.9
N_1	(133)	(123)	(36)	(24)	(9)	(5)	(102)
Species cultured[2,3]							
Eastern/Pacific oysters	67.7 (75.9)	87.9	72.7	36.0	44.4	33.3	0
Flat (Kumamoto/Olympia) oysters	9.8 (20.3)	3.2	0	0	0	0	0
Mussels	16.5	4.0	0	0	0	0	0
Quahogs/hard (manila) clams	10.5 (34.6)	5.2	75.8	88.8	100	100	92.4
Sea scallops	0.8	0.8	0	0	0	0	0
Bay scallops	0.8	10.5	6.1	0	0	0	0
Other (Geoducks)	9.2 (15.0)	8.1	12.1	4.0	0	0	10.4
N_2	(133)	(124)	(33)	(25)	(9)	(6)	(106)
Culture methods[2]							
Suspended lines	26.2	11.8	5.1	40.0	11.1	16.7	0.9
Bottom cages (metal)	2.8	40.2	33.3	0	11.1	33.3	1.8
Bottom cages (plastic)	16.3	26.0	12.8	8.0	55.6	16.7	1.8
ADPI	1.4	51.2	35.9	12.0	22.2	50.0	0
Other mesh	14.2	11.8	23.1	48.0	22.2	50.0	48.2
Rafts	11.3	10.2	12.8	0	0	16.7	0
Racks	19.9	31.5	28.2	8.0	22.2	0	0.9
No structure – directly on bottom	46.1	30.7	30.8	44.0	33.3	16.7	15.8
Hatchery	7.8	13.4	15.4	8.0	33.3	0	7.0
FLUPSYs	9.9	32.3	17.9	0	33.3	0	4.4
Aqua purse	7.1	1.6	0	0	11.1	0	2.6
Lantern/pearl nets	10.6	7.9	0	0	0	0	0
Suspended bags/cages (plastic)	14.9	21.3	10.3	4.0	11.1	16.7	8.8
Suspended bags/cages (wood)	0	3.1	0	0	0	0	0
Stacked cages, suspended in water column	10.6	9.4	5.1	0	0	0	0
Chinese hats	2.1	8.7	0	0	0	0	0
Other	17.0	9.4	12.8	8.0	33.3	0	48.2
N_3	(141)	(127)	(39)	(25)	(9)	(6)	(114)

[1]The number of years the respondent had been in the shellfish culture business.

[2]The percent of respondents to specific question i (N_i) who cultured that species or engaged in that specific culture method. Note that the percentages for each descriptor, by region, do not sum to 100, because some respondents selected more than one choice for species and/or culture method.

[3]The numbers in parentheses for Species Cultured describe the percentage of respondents who cultured the West Coast species, whose respective italicized names also appear in parentheses.

southeastern states refers almost entirely to the use of such soft-mesh bags.

Biofouling as a Production Problem

Survey respondents were asked to evaluate biofouling within their production system on several levels: degree of problem, changes in biofouling over time, and specific production problems caused by biofouling (Table 3).

How Problematic is Biofouling? Respondents were asked if biofouling was a constant, periodic, or nonexistent problem for their overall culture production system. Across all samples, 58.9% of the respondents indicated that biofouling was "somewhat/periodically" a problem, 27.9% indicated biofouling was a "big problem/constant issue," while 9.9% responded that biofouling was not a problem. These findings varied across regions. For example, 40.2% of the respondents in the Northeast coast sample indicated that biofouling was a big problem, while 27.9 and 17.5% of the respondents in the Florida and West Coast, respectively, indicated that the biofouling was a big problem. A greater percentage of respondents from the

TABLE 3. *Biofouling as a production problem, by region.*[1]

	West Coast	Northeast Coast	Virginia	North Carolina	South Carolina	Georgia	Florida	Total
Production-related problem?								
Somewhat/periodically	55.5	51.2	71.8	72.0	55.6	83.3	62.2	58.9
Big/constant issue	17.5	40.2	21.5	20.0	22.2	16.7	27.9	26.5
Not at all	27.0	8.6	7.7	8.0	22.2	0	9.9	15.2
N_4	(138)	(129)	(39)	(25)	(9)	(6)	(111)	(457)
Changed over past 5 years?								
Increased	18.1	35.5	20.0	30.0	11.1	50.0	33.3	27.9
Decreased	3.9	3.6	0	0	0	16.7	3.6	3.4
About the same	78.0	60.9	80.0	70.0	88.9	33.3	63.1	69.2
N_5	(127)	(110)	(35)	(20)	(9)	(6)	(111)	(418)
Problematic issues created[2]								
Reduced water flow-through	45.9	79.4	83.3	60.9	75.0	66.7	71.4	66.4
Crowding	18.5	18.3	8.3	4.3	37.5	33.3	15.2	16.6
Reduced survival	48.1	46.8	47.2	34.7	62.5	33.3	69.9	50.2
Reduced growth	47.4	71.4	63.9	56.5	62.5	50.0	66.1	60.9
Increased predation	9.6	11.9	2.8	4.3	12.5	0	14.3	10.5
Increased disease	5.2	12.7	2.8	4.3	12.5	0	3.6	6.7
Increased size distribution	10.4	21.4	13.9	4.3	37.5	0	22.3	16.8
Other	17.0	13.5	8.3	13.0	0	16.7	9.8	13.0
None	25.9	7.9	8.3	8.7	12.4	0	8.0	13.5
N_6	(135)	(126)	(36)	(23)	(8)	(6)	(112)	(446)

[1]The percent of respondents to specific question i (N_i) who selected a specific choice.
[2]Note that the values for each region do not sum to 100, because some respondents selected more than one choice.

West Coast sample (26.8%) indicated, however, that biofouling was not a problem. For all regions, most respondents indicated that biofouling was a periodic or constant problem.

Has Biofouling Changed Over Time? Respondents were asked if biofouling had become more or less of a problem over the past 5 years. Overall, 27.9% of the total respondents indicated that biofouling had become more of a problem, while 69.2% indicated there had been no change. This pattern was reflected by most of the regional samples, with the exception of Georgia.

Specific Production Problems Created. The survey respondents were presented with a variety of potential production problems that might be created by biofouling. The majority of the respondents across all regions indicated that "reduced water flow-through" (66.4%), "reduced survival" (50.2%), and "reduced growth" (60.9%) were the most problematic issues associated with biofouling. Of lesser importance were "increased size distribution" (16.8%) and "crowding" (16.6%). This ranking of problematic issues was in general common across all regions, with some variation amongst the ranking of the top three issues. Crowding, disease, and predation were deemed to be of lesser importance, though some of these issues due to biofouling are likely linked in some manner within the overall scope of the production system (i.e., crowding → reduced growth → increased size distribution).

Currently Utilized Biofouling Control Methods

A wide range of methods are used by shellfish growers to control biofouling (Table 4). The methods exhibit considerable commonality, even across survey regions. Some regional differences exist, which was due to the differing types of gear being used with each area, as well as the site-specific environmental conditions that were conducive to the growth of fouling organisms. The primary forms of control typically utilize significant amounts of labor

TABLE 4. *Selected biofouling control methods by region.*[1]

State/Region	Selected biofouling control methods
West Coast	Mechanical scraping/scrubbing/brushing, timing of planting to avoid barnacle set, power washing, frequent gear cycling, air-drying of gear, fresh water dip, flipping bottom gear, hand removal, harrowing
Northeast Coast	Power washing, flipping floating bags, netting changes, hand culling, air-drying bags, scrub out FLUPSYs, UV exposure, squeegee nets, brine dips, lime dips, gear rotation, use vinyl wire cage material, brush bags, bleach scrub, intertidal exposure
Virginia	Pressure washing, sweep nets with brooms, flipping gear, exposure to sunlight, rotate gear, air exposure, high-salinity dip
North Carolina	Replace mesh covers, freshwater rinse, rake algae, rotating gear, sweep/brush nets, flipping gear, hand scrape
South Carolina	Washing and scraping, squeegee netting, hand cleaning with scrapers
Georgia	Hand scrubbing
Florida	Chlorine bath, pressure washing, timing of plants, manual cleaning, cover netting, rotate gear, dipping, discard removed fouling away from lease area, brush bags, use water-based dipped bags, use larger mesh, fresh water rinse

[1]The methods listed represent a select set of control methods. This does not represent an exhaustive list of the methods as provided by all respondents. The order of listing does not imply frequency of response, preference by respondents, or exclusivity of use by region.

and energy, both of which add to the overall cost of operation.

Costs Associated with Biofouling Control

A primary purpose of the survey was to assess the types and magnitudes of costs expended by shellfish growers in their efforts to control biofouling. Thus, respondents were asked if biofouling, in general, increased their production costs, and, if costs had increased, then respondents were asked to identify which types of costs were impacted. Finally, respondents were asked to estimate what percentage of their total annual, operating expenses was associated with efforts to "deal" with biofouling (Tables 5 and 6).

Does Biofouling Increase Costs of Operation? Of the total respondents across all regions, 78.5% indicated that biofouling increased operational costs (Table 5). Within regions, 89.2% of the Virginia respondents indicated that biofouling increased costs (the highest value),

TABLE 5. *Cost implications associated with biofouling, by region.*[1]

	West Coast	Northeast Coast	Virginia	North Carolina	South Carolina	Georgia	Florida	Total
Does biofouling increase cost of operation?								
Yes	64.4	87.2	89.2	68.2	77.8	66.7	85.5	78.5
No	35.6	12.8	10.8	31.8	22.2	33.3	15.5	21.5
N_{8a}	(132)	(125)	(37)	(22)	(9)	(6)	(110)	(442)
If "Yes," what costs affected?[2]								
Repair and maintenance	33.6	54.1	69.7	47.1	57.1	50.0	81.3	62.1
Labor	89.8	89.9	90.9	88.2	85.7	66.7	80.2	86.8
Fuel/energy	39.8	38.5	45.5	17.6	28.6	50.0	44.8	40.2
Marketing/packaging	17.1	9.2	6.1	0	0	0	12.5	11.0
Other	22.7	9.2	0	17.6	28.6	0	17.7	14.6
N_{8b}	(88)	(109)	(33)	(17)	(7)	(6)	(96)	(356)

[1]The percent of respondents to specific question i (N_i) who selected a specific choice.

[2]Note that the values for each region may not sum to 100, because some respondents may have selected more than one choice.

TABLE 6. *Estimated annual costs ($) associated with biofouling, by region.*

	West Coast	Northeast Coast	Virginia	North Carolina	South Carolina	Georgia	Florida
% Total operating costs[1]	10.4	20.4	11.6	12.3	7.3	5.0	13.9
N_{9b}	(53)	(72)	(22)	(11)	(3)	(1)	(66)
Total biofouling costs[2]	706,986	1,202,770	342,050	4050	84,540	3500	311,108
Average biofouling costs[3]	20,200	23,130	21,380	405	16,908	1750	6619
$N_{9a,b}$[4]	35	52	16	10	5	2	47

[1]The average percent of total annual operating costs associated with biofouling control across all respondents to question 9b, or N_{9b}.

[2]The total annual costs associated with biofouling control ([response to question 9a multiplied by 9b for each respondent] and summed across only those respondents as defined in footnote 4 below).

[3]The average annual costs (TBC/$N_{9a,b}$) associated with biofouling control amongst only those respondents as defined in footnote 4 below.

[4]The number of respondents who provided information for both questions 9a and 9b.

while 64.4% of the West Coast respondents indicated that biofouling increased costs (the lowest value). On a percentage basis, fewer growers in the West Coast, North Carolina, and Georgia samples experienced increases in costs because of biofouling.

What Costs are Affected? If a respondent indicated that production costs were impacted by biofouling, the types of costs most affected by biofouling was solicited (Table 5). For the entire set of respondents across all samples, the costs most likely (% of respondents indicating an impact) to be affected by biofouling include "labor" (86.8%), "repair and maintenance" (62.1%), and "fuel / energy" (40.2%). Most respondents indicated that labor was a cost affected by biofouling across all samples, with the highest percentage in Virginia (90.9%) and the lowest in Georgia (66.7%). Marketing was a cost impacted more for producers on the West Coast, Northeast, and Florida. Other "costs" that were affected by biofouling included "culling effort," "dipping costs," "buying more seed," "disposal costs," and "loss due to mortality."

Estimated Annual Costs Associated with Biofouling. The study hypothesized that the costs associated with controlling biofouling within molluscan culture systems were not insignificant regardless of the region in which the culture process occurs. Respondents were first asked to estimate their total annual *operating* costs (excluding depreciation, long-term loan interest, and other overhead expenses). Then, respondents were asked to estimate the percentage of their total operating costs that were associated with efforts to deal with biofouling. That percentage ranged from 5.0% in Georgia to 20.4% in the northeast region (Table 6). The average percentage of total operating costs across all regions dedicated toward dealing with biofouling was 14.7%. The sample-specific percentage was then applied to the total annual operating cost for each region to derive the total annual cost that is expended while dealing with biofouling. These values represent the average annual biofouling-related costs across the respondents for each region. The values were somewhat similar for the West Coast, Northeast, and Virginia ($20,200, $23,130, and $21,380, respectively). North Carolina exhibited the smallest average cost ($405). The biofouling-related cost for South Carolina ($16,908) was approximately 2.5 times that found for Florida ($6619). The average annual biofouling-related cost for the Georgia respondents was $1750.

Marketing Implications Associated with Biofouling. Respondents were asked if biofouling had any impact on their ability to market their product, and, if so, how? Of all the survey respondents, 43.4% indicated that biofouling affected the marketability of their products

(Table 7). A greater percentage of the Florida respondents (57.1%) indicated that biofouling had marketing impacts, while only 16.7% of the North Carolina respondents indicated a marketing impact. Approximately 41% of the respondents within the West Coast, Northeast coast, and Virginia indicated a market impact due to biofouling.

Marketing-Related Attributes Affected. Although biofouling appeared to play an important role in the marketability of cultured shellfish, the survey also sought to identify the specific marketing attributes impacted by biofouling (Table 7). Across all survey regions, most respondents indicated that biofouling resulted in an unsightly appearance of the product (57.3%) and a greater number of buyer rejections (21.4%). The relative importance of the impact of biofouling on the marketing attributes varied somewhat by region. For example, West Coast respondents also indicated that decreased meat yield was a problem (23.3%). Respondents from the East coast and Virginia indicated that although appearance was an issue, the increase in size distribution and decreased shelf-life were also affected. Few respondents from North Carolina, South Carolina, and Georgia provided input on this particular question to provide much insight for those regions; however, the survey findings do suggest that biofouling can have an impact on the growers ability to market the product effectively, generating an additional financial impact on the business, aside from the costs of direct control.

Discussion

Commercial aquaculture is a highly competitive industry in the USA. Identifying methods with which to control operational costs is vital in not only competing with domestic producers, but also with foreign suppliers. Molluscan shellfish growers are no exception to this situation. Controlling biofouling is a costly process for shellfish growers; however, the magnitude of the costs associated with biofouling has not previously been estimated for molluscan shellfish growers in the USA. Understanding the impact that biofouling has on shellfish aquaculture will simulate future research aimed at developing effective means by which to control and mitigate biofouling in molluscan shellfish operations.

Our survey was designed to assess the degree to which biofouling creates constraints and costs related to production and marketing for molluscan shellfish growers in the USA. The survey was sent to 1375 individual

TABLE 7. *Marketing implications associated with biofouling, by region.*[1]

	West Coast	Northeast Coast	Virginia	North Carolina	South Carolina	Georgia	Florida	Total
Does biofouling affect the marketability of your product								
Yes	40.6	41.5	40.5	16.7	25.0	33.3	57.1	43.4
No	59.4	58.5	59.5	83.3	75.0	66.7	42.9	56.6
N_{10a}	(133)	(118)	(37)	(24)	(8)	(6)	(112)	(438)
If "Yes," what marketing issues are affected?[2]								
Unsightly appearance	71.7	72.5	75.0	100.0	11.1	100	38.9	57.3
Increased size distribution	16.7	25.5	25.0	0	22.2	0	14.2	18.1
Decreased selling price	13.3	17.6	6.3	0	11.1	100	10.6	13.3
Increased buyer rejections	28.3	17.6	18.8	33.3	0	0	20.4	21.4
Decreased shelf-life	11.7	19.6	50.0	33.3	11.1	0	18.6	19.4
Decreased meat yield per animal	23.3	19.6	12.5	33.3	0	0	12.4	16.9
Other	15.0	25.5	12.5	33.3	11.1	0	8.8	14.5
N_{10b}	(60)	(51)	(16)	(3)	(3)	(2)	(113)	(248)

[1]The percent of respondents to specific question i (N_i) who selected a specific choice.

[2]Note that the values for each region may not sum to 100, because some respondents may have selected more than one choice.

molluscan shellfish growers in 7 geographic regions. An overall response rate of 37% provided 510 usable surveys. The findings show that biofouling was a periodic or constant issue with growers, and created a wide range of production-related problems, such as reduced water flow, reduced survival, decreased growth rates, increased size distribution with bags and cages, and other issues. Growers used a wide range of biofouling control methods, most of which require significant labor or energy/utilities to conduct. The majority of the survey respondents indicated that biofouling increased their production costs, particularly with respect to repair and maintenance, labor costs, and fuel/energy. Biofouling also represented a sizable component of the total annual operating costs. Across all survey respondents, efforts to control biofouling accounted for an average of 14.7% of the total annual operating costs. These costs varied by region, with respondents in the northeast coast region indicating that 20.4% of the annual operating costs ($23,130) are related to biofouling control, while respondents in Florida reported a 13.9% share of costs ($6619) directed to biofouling control. Extrapolating the average biofouling costs by region across the total populations of molluscan growers within the respective regions and then summing the resulting regional totals provide an overall total value of $21,611,000 in costs associated with controlling biofouling by US molluscan shellfish growers. This admittedly rough estimate provides some preliminary insight into the magnitude of costs that biofouling creates for shellfish growers.

In addition to direct costs associated with control efforts, biofouling can impact revenues by reducing the marketability of the harvested shellfish. Across all sample regions, 43.4% of the respondents indicated that biofouling affected the ability to market product. The primary market attributes affected included product appearance, size distribution, and buyer rejections.

Biofouling has an impact on the costs of operation and marketability of harvested product for molluscan shellfish growers. Research focused toward developing cost-effective methods to control and mitigate biofouling in shellfish culture systems should pay high dividends to the industry. Reducing the costs and marketability constraints associated with biofouling would assist domestic molluscan shellfish growers in retaining their share of increasingly competitive world and domestic markets.

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