Aquaculture 515 (2020) 734569

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Performance and conduct of supply chains for United States farmed oysters

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ARTICLE INFO

Keywords:
Chesapeake bay
Oyster
Shellfish
Supply chain
Traceability
Washington

ABSTRACT

Farmed oysters are one of the most valuable aquacultured products in the United States (U.S.), are highly perishable, and increasingly shipped live year-round. Supply chain actors must work together to bring refrigerated oysters to market quickly, while maintaining product value, safety and traceability information. In light of these demands, this study assesses the performance and conduct of supply chains for U.S. farmed oysters (*Crassostrea virginica, C. gigas*). Over the two-year study period, we conducted interviews with 56 businesses and tracked 125 oyster shipments from two major growing regions in the U.S. through six different types of supply chains. We hypothesized that direct and intermediated supply chains would perform differently in terms of time-to-market, product temperature in cold chains, compliance with temperature regulations, and modeled risks from *Vibrio parahaemolyticus*. Intermediated supply chains, by their definition have more connections than direct supply chains, and we found this introduces a longer time-to-market and a higher incidence of time and temperature abuse. However, these factors did not lead to greater modeled *V. parahaemolyticus* risks. Participants in both direct and intermediated supply chains were aware of the importance of traceability and felt uniformly positive about their ability to perform recalls. A common concern was the speed of government-imposed recalls, which can be declared by regulators after the affected live oysters are consumed. Members of these supply chains play different roles in maintaining the cold chain, possess different levels of information related to traceability, and describe different levels of trust with other supply chain actors. This paper contributes to a growing body of knowledge on supply chains for seafood and their critical, and sometimes overlooked, role in larger food systems.

1. Introduction

Supply chains connect producers and consumers and facilitate the exchange of products, money, and information. Traceability can support efficient supply chain functioning and is increasingly seen as important to manage inventory, logistics, risk, enhance food safety, prevent fraud, reduce waste, and add value to products (Aung, Chang, 2014; Bailey et al., 2016; Bosona, Gebresenbet, 2013; Iles, 2007; King, Venturini, 2005; Leal et al., 2015; Lewis, Boyle, 2017). Studies of seafood supply chains are expanding in scope beyond traditional economic measures to include transparency, forced labor, equity, food safety, and other topics, and researchers are beginning to think about seafood as part of larger food systems (Olson, Clay, Pinto da Silva, 2014).

The focus of this study is aquacultured oysters raised in Washington State and the Chesapeake Bay, the largest molluscan shellfish farming regions in the United States (U.S.) (NOAA, 2017; USDA, 2014). Oysters are the most valuable marine aquaculture species in the U.S., valued at $173 million in 2015 (NOAA, 2017). Previous work with molluscan shellfish supply chains in the U.S. has mainly focused on production, farm gate sales, and economic impact (Augusto, Holmes, 2015; Hudson, 2017; Hudson, Murray, 2014; Northern Economics Inc., 2013). Supply chains are not reported in the Census of Agriculture, the major survey of U.S. aquaculture that occurs every five years (USDA, 2014). A separate U.S. government survey was conducted on food marketing, however, aquaculture products were not reported (USDA, 2016). Hence, little is known about supply chains for U.S. aquaculture products, and

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https://doi.org/10.1016/j.aquaculture.2019.734569
Received 26 March 2019; Received in revised form 1 October 2019; Accepted 3 October 2019
Available online 14 October 2019

specifically molluscan shellfish, notwithstanding that these products are highly traceable (NSSP, 2015).

Industry experts report that the dominant way live oysters are marketed in the U.S. is via intermediated supply chains, which are supply chains involving intermediaries like wholesalers, trucking companies, commercial airlines, freight forwarders, importers/exporters, and distribution centers for chain restaurants and retailers. Direct supply chains involve marketing directly to consumers, retailer, or institutions, are used less frequently and to sell smaller quantities of product. Oyster farmers participate in both direct and intermediated supply chains, sometimes simultaneously. Seafood producers in the U.S. and elsewhere are being encouraged to try direct marketing because they can receive a greater share of the retail price by taking over distribution and sales functions (Chase, Otts, 2016; Johnson, 2018; Stoll et al., 2015) (Bjørndal et al., 2015), however there are also drawbacks because direct sales require new skills, an interest in marketing, and can be time consuming (King et al., 2010). Shellfish producers, who are often small businesses, can benefit from knowing the strengths and limitations of different marketing approaches.

In this study, the first research question we asked was: how do businesses interact with each other in supply chains, and what are their conduct, behavior, and perceptions regarding aspects of food safety and quality? Previous studies suggest that cooperation and communication can improve food quality and safety and reduce food waste (Gobel et al., 2015; Wang et al., 2015), and we wanted to explore these concepts with molluscan shellfish. A second research question we asked was: does supply chain configuration affect its performance? This research question is grounded in previous work on food supply chains for meat, dairy, fruit, and vegetables, in which supply chain configuration (direct, intermediated, mainstream supply chains) does affect some measures of performance (King et al., 2010). King and colleagues found that local food supply chains put more emphasis on social capital creation and civic engagement, and producers in these supply chains receive higher revenues per unit product and retain a larger share of the retail price. We categorized supply chains as either intermediated or direct supply chains, and performance measures focused on indicators of product freshness, safety, and quality. These findings can directly assist the molluscan shellfish industry, as well as provide broader insights about seafood distribution systems, particularly among downstream parts of the supply chain (e.g., wholesale and retail) that are not considered in most aquaculture research.

2. Methods and materials

2.1. Study design

Our general approach was modeled after work by King and colleagues (King et al., 2010) and influenced by food systems methodology (Institute of Medicine, National Research Council, 2015). We employed a mixed-methods study with two components: i) interviews of oyster supply chain businesses to better understand their views and perceptions; and ii) assessments of the performance of these supply chains by tracking oyster shipments (time in transit, food kilometers traveled, product temperature, and Vibrio modeling) from harvest until delivery to retail or restaurant customers. The study was stratified by recruiting a mixture of oyster producers engaged in direct and intermediated supply chains within the study regions.

The study regions were the Chesapeake Bay and Washington State, which contain 30% of all U.S. businesses certified to produce, process, and distribute molluscan shellfish (Fig. 1). The Chesapeake Bay portion of the study was conducted from January to September 2017 and focused on farmed Eastern oysters (*Crassostrea virginica*) harvested from Virginia or Maryland and marketed regionally and nationally. The Chesapeake Bay region spans multiple states and is a more relevant geographic unit than state boundaries. The Washington State portion of the study ran from February to October 2018 using Pacific oysters (*C. gigas*). For Washington State, we tracked shipments made locally (within Washington State), nationally, and internationally.

2.2. Survey tool and participant recruitment

We developed a survey tool to collect information about the structure, conduct, and performance of oyster supply chains. The survey was modified with input from 12 experts, including a representative from state and federal agencies, regional industry associations, food businesses, and academia. The survey was piloted with four participants who were excluded from the full study.

Participants were recruited into the study using chain sampling methods, starting with oyster producers and wholesalers, and then recruiting their upstream and downstream customers. Participants were contacted by phone or email and given a one-page description of the study and a consent form. As an incentive, we provided participants with data about the performance of their own cold chain. The inclusion criteria were: employee of an active business in a Washington State or Chesapeake Bay oyster supply chain, 18 years of age or over, English speaker, and agreeing to participate in the study. We excluded all wild-caught oysters as well as oysters harvested outside of the Washington State and Chesapeake Bay regions. The study was reviewed by the Johns Hopkins School of Public Health Institutional Review Board.

The survey was performed as an in-person or phone interview. After the first year of the study we reorganized and modified the survey questions to improve question flow and added questions about traceability. The survey tools are provided in the Supporting Information section.

2.3. Oyster temperature tracking and Vibrio modeling

The methods for oyster temperature tracking have been described previously (Love et al., 2018, 2019). Briefly, we taped coin-sized temperature data loggers onto boxes of oysters and inserted them into live oysters traveling in the same oyster boxes. Sensors were deployed on farms and ultimately removed by retail or restaurant staff and returned to the study team using pre-paid envelopes. We recorded the product time-in-transit and the names and addresses of all businesses that handled shipments. The methods for *Vibrio parahaemolyticus* modeling have been described previously (Love et al., 2018, 2019).

2.4. Data analyses

Notes were taken during each interview and shared with interviewees to check for accuracy. Descriptions of interviewee responses were entered into a spreadsheet in Excel (Microsoft Corp., Redmond, Washington) that was used for data management and analysis. A member of the study team reviewed and analyzed responses to each question by group (e.g., producers) in the supply chain to identify key themes and consistent experiences and perceptions, as well as differences within groups and across supply chains. Then, study team members followed an iterative process to summarize these results and prioritize information that was informative and highly relevant to the research aims. A limited number of quotes were included in the results to capture interviewees' own words. In the results, we grouped responses to maintain the anonymity of respondents. Direct quotes were not attributed to individuals.

3. Results

3.1. Study participants

The study population was 143 businesses that participated in the Washington State and Chesapeake Bay oyster supply chain study

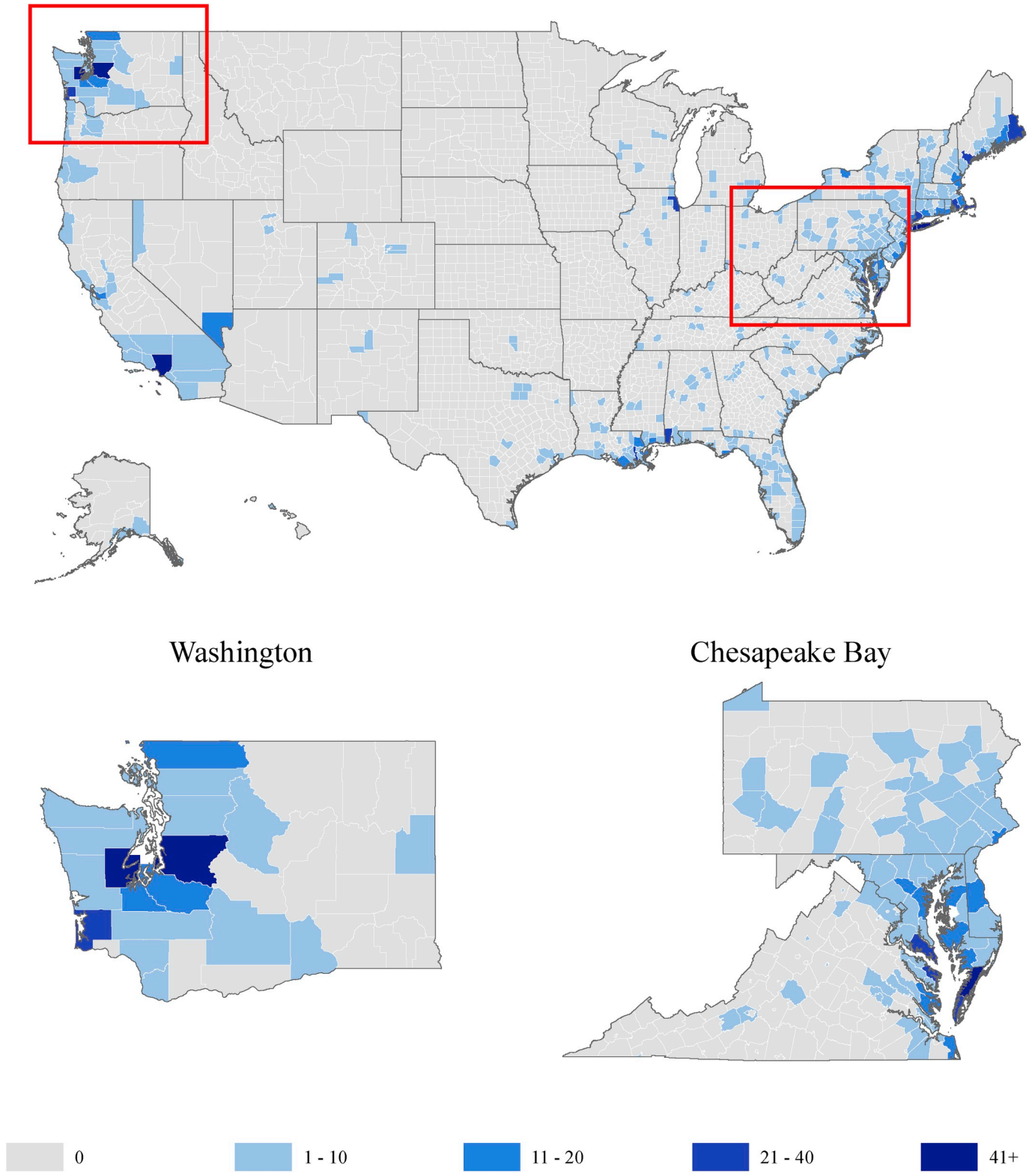

Fig. 1. Certified shellfish producers, processors, and distributors by county. Data collected September 2017 (FDA, 2017).

representing six different types of supply chains (Fig. 2). We interviewed 56 of 143 businesses (39% response rate) with good representation among the different stages of the supply chain (Table 1). Participants were located in California, Colorado, Florida, Georgia, Hawaii, Illinois, Maine, Maryland, Massachusetts, Oregon, Pennsylvania, Tennessee, Virginia, and Washington State (participant location is not disclosed to maintain anonymity).

3.2. Supply chain structure

We asked a series of questions about the structure and size of these supply chains (summarized in Table 1, Fig. 2, and Supporting Information Fig. 1S). Producers sell the majority of oysters to intermediated supply chains, while maintaining some direct sales. Producers in Washington State sell a variety of molluscan shellfish species (e.g.,

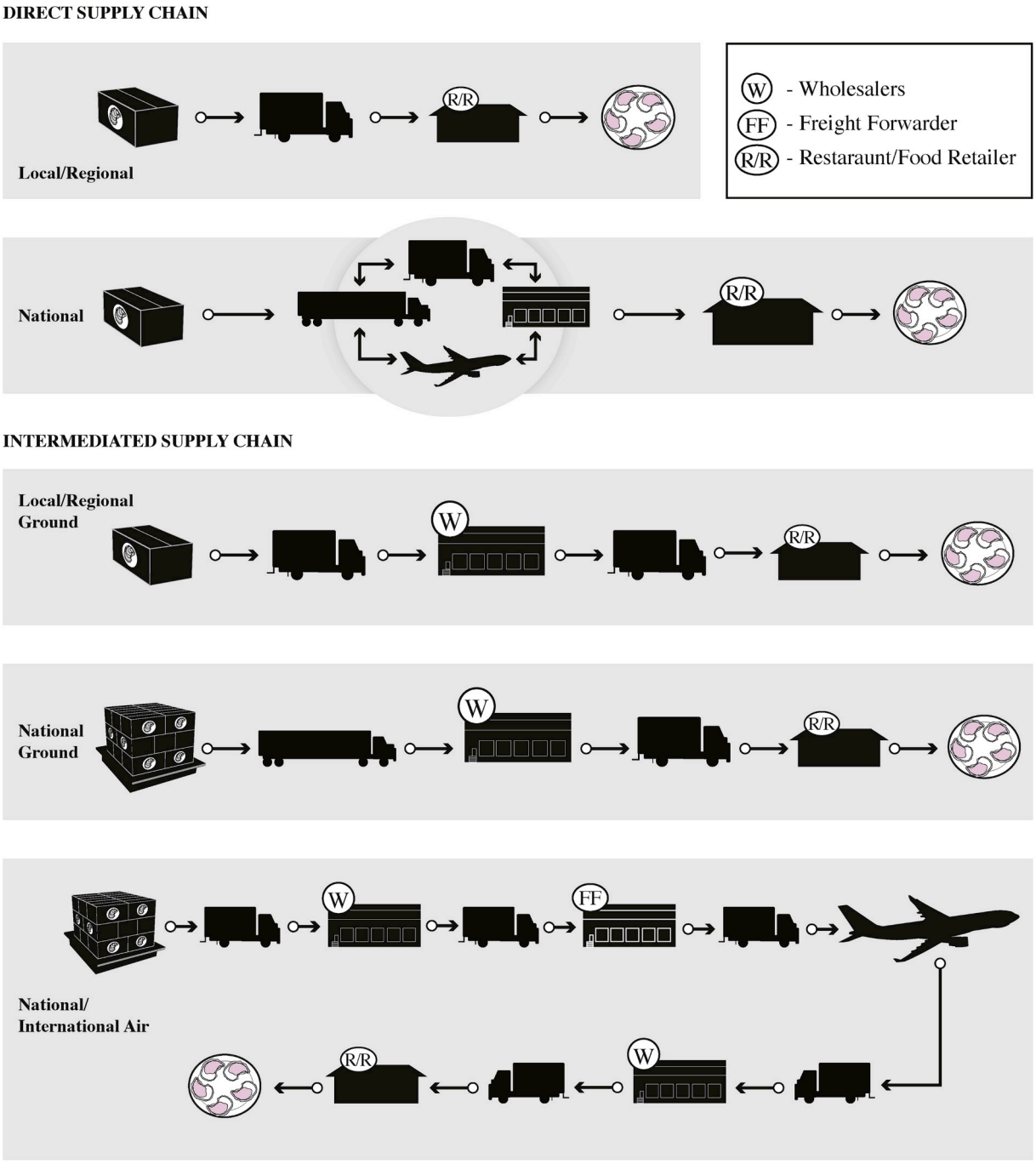

Fig. 2. Direct and intermediated supply chains for U.S. farmed oysters. The figure was created by tracking the supply chains for 125 oyster shipments made by participants. W = wholesale; FF = freight forwarder; R/R = restaurant and/or food retailer.

oysters, clams, mussels, and geoducks), while Chesapeake Bay producers who participated in the study focused mainly on oysters. Oyster producers on both coasts harvest and ship from two to five days per week with larger businesses harvesting more often.

Most restaurants and food retailers source oysters from wholesalers because it is convenient to order oysters from multiple growing regions from a single vendor and to have multiple ordering opportunities each week, but some restaurants prefer to order directly from producers for a variety of reasons (e.g., fresher products, faster delivery, connection to the farmer, marketing as a *locavore* restaurant).

Several types of vertically integrated businesses participated in this study. A handful of producers raise seed oysters or fabricate aquaculture equipment that are used by their business and/or sold as a side business. Several producers also purchase market-sized shellfish from smaller farms and act as dealers or wholesalers, which may require expanded refrigeration capacity, a wet storage facility, or an off-site distribution center. Half of the producers in the study own, operate, or are affiliated with a restaurant or raw bar, which provides an additional outlet for sales and can enhance the visibility of their brands.

3.3. Roles, expectations, and interactions among businesses

A clear understanding of the roles, expectations, and preferences among members of the cold chain is critical for maintaining food

Table 1
Participants and background information on customers and sales.

Supply chain stage	N [a]	Oyster sales, average (range)		Sales outlets and customers
		Thousand pieces per week	As % of total sales	
Producer				
Washington State	6	129 (14–600)	37 (20–80)	90–99% to wholesaler,
Chesapeake Bay	6	53 (10–163)	100 (99–100)	1–10% to direct market
Wholesaler				
Broadline seafood	9	38 (4–65)	11 (5–20)	food retailer, restaurant, or small wholesaler
Shellfish-specific	3	73 (40–130)	78 (60–90)	seafood distributor, other wholesalers
Freight Carrier	9	n/a	n/a	all other businesses
Food Retailer and Restaurant	23	2 (0.15–12)	15 (1–30) [b]	restaurant patrons, grocery store customers, seafood market customers

[a] Participants interviewed: Wholesale (n = 9 WA, n = 3 CB); Freight Carrier (n = 5 WA: 4 air freight carriers, 1 freight forwarder; n = 4 CB: 3 ground freight carriers, 1 direct to consumer freight company); Restaurant/Food Retail (n = 10 WA, n = 13 CB); Total (n = 30 WA; n = 26 CB). (WA = Washington; CB = Chesapeake Bay).
[b] As a percent of total food sales.

quality and safety. Producers wash, grade, box oysters, and cool them after harvesting. They are legally required to harvest and cool products following strict time and temperature parameters (NSSP, 2015). Producers prefer using refrigerated ground freight for deliveries within the East Coast and West Coast, while deliveries to the Midwest or Mountain West use a mixture of air and ground freight depending upon the destination, price, and customer preferences. Cross-country deliveries and shipments outside of the continental U.S. are handled exclusively by air freight. Producers report that they can ship anywhere in the country, but logistics drive price. One producer noted that it is more profitable to ship by truck, however, at the request of industry stakeholders, we did not ask for economic data.

Ground freight companies see their role as maintaining the temperature of the product, not cooling product. One trucking company representative said, "We just pick up and drop off, if we pick up products at 4 °C they are going to be 4 °C when we deliver them." For airline shipments and direct-to-consumer freight, customers are asked to prepare and pack the shipment as if it would be unrefrigerated for up to 48 h for domestic trips and 72 h for international trips (American Airlines, 2018; Delta, 2018; Fed Ex, 2017). Wholesalers have the most sophisticated refrigeration systems and act as hubs in intermediated shellfish supply chains. Some wholesalers use time-temperature indicators (TTIs) or temperature data loggers for oyster shipments and others do not. Restaurants and retailers have a responsibility to check for product quality and take the temperature of the product upon arrival and store the product in a refrigerator or on ice until it is served to customers.

Participants have mixed views on trust (or a lack of trust) between businesses in the supply chain, which sets the tone for how businesses interact. For example, one chef noted their relationship with wholesalers is "usually not very friendly and there can be a lot of distrust" and another said "wholesalers are just sending you whatever they have in their inventory" implying that they could be unloading old products. This led some chefs to be vigilant about product quality, source from multiple wholesalers to extract better prices, and return products frequently in the beginning to signal to the wholesaler that the restaurant was paying attention and had high standards for product quality. Other chefs felt there was trust and shared values with their wholesalers and treated them as long-term business relationships. One wholesaler characterized his work as a "team effort" with his suppliers and customers to maintain value along the supply chain. There were many examples of coordination between producers and wholesalers or retailers, and in some cases, there was long-term strategic cooperation, for example farms working with restaurants to develop exclusive brands of oysters.

3.4. Perceptions of product quality attributes

Intermediated supply chains have three to seven businesses involved in bringing products to market (Fig. 2), and there is potential for asymmetry in information. We asked the producers and retailers in the supply chain what they consider to be important product attributes. In general, we found there was good agreement between these groups (Table 2), although there were some notable mismatches. A common opinion summarized by one chef is, "The product has to be perfect all the way through." Juxtaposed to this view, several producers noted that working with chefs is an effort in "managing expectations" because products are unique, may change seasonally, and may have imperfections such as barnacles, worms, or oyster crabs on or inside the oyster. Restaurants are attuned to the ease or difficulty of shucking oysters and whether the product breaks while shucking. For example, one raw bar buyer noted, "When you blow through a thousand oysters on a Friday night, you need something that is easy to shuck." However, producers rarely market their products based on shuckability or shell strength.

Table 2
Quality attributes mentioned by oyster producers, restaurant chefs and food retailers [a].

Producers	Restaurant and Food Retailers
Oyster-specific:	**Oyster-specific:**
• Cleanliness	• Cleanliness
• Consistency	• Exclusive product line
• Deep cup	• Freshness
• Salinity	• Meat that fills the cup
• Shuckability	• Nice looking oyster
• Unique grow-out methods	• Salinity
Marketing and sales:	• Shuckability
• Attractive packaging	• Shell quality
• Branding and storytelling	• Taste and texture
• Large volumes for sale	• Unique brand name
• Reliability	**Marketing and sales:**
• Reputation	• Customer experience
• Same day shipments	• Knowledgeable staff
• Unique brand name	• Locally sourced oysters
• Year-round sales	• Menu rotates frequently
Other:	• Price
• Economic sustainability	• Sourced from a reputable seller
• Environmental sustainability	• Variety of oysters available (geography and salinity)
• Food safety	• $1 happy hour oysters

[a] These responses came from the Chesapeake Bay oyster supply chains. The questions were removed from the Washington state survey in year two to allow room for new questions.

Table 3
Food kilometers, food quality, and safety in U.S. farmed oyster supply chains.

Supply Chain (delivery mode)	N [a]	Delivery (± st dev)			Percent of shipments (%)	
		Avg time (days)	Median distance (km)	Temperature (°C)	Time-temperature abuse	*Vibrio parahaemolyticus* growth
Direct Sales						
Local/Regional [b] (ground)	14	1.1 ± 1.0	34	5.1 ± 2.9	14	29
National (air, ground)	11	1.6 ± 1.0	1914	3.6 ± 1.9	0	36
Direct Sales, sub-total	25	1.3 ± 1.0	143	4.4 ± 2.6	8	32
Intermediated						
Local/Regional [b] (ground)	34	3.5 ± 1.8	429	4.5 ± 4.2	18	29
National (air)	15	3.5 ± 1.4	5097	5.4 ± 2.1	33	33
National (ground)	15	5.0 ± 1.8	1389	3.0 ± 1.4	13	0
International (air)	2	3.5 ± 0.1	10,606	5.8 ± 0.2	100	0
Intermediated, sub-total	66	3.8 ± 1.8	641	4.4 ± 3.3	23	23
Total	91	3.1 ± 2.0	504	4.4. ± 3.1	19	25

[a] Number of oyster shipments tracked.
[b] Local (Washington State); Regional (Cheseapeake Bay).

3.5. Supply chain performance

A separate research question explored the hypothesis that supply chain configuration (intermediated vs direct supply chains) can affect food quality and safety. To answer this question, we measured time-to-market, product temperature, and compliance with regulations, and we modeled risks from *Vibrio parahaemolyticus* (Table 3).

Oysters are live, perishable products and therefore rapid deliveries under controlled temperatures give retailers longer shelf-life. We used time-to-market as an indicator of freshness of a product. Comparing direct supply chains to intermediated supply chains, intermediated supply chains had significantly slower time-to-market than direct supply chains (T-test; $p = 0.0001$), and the difference appears to be the presence of the wholesalers in the supply chain. Wholesalers add an additional 1.8 days to the time-to-market, which could be caused by inventory control or the time lag between receiving product and fulfilling new orders. Within intermediated supply chains, transportation modes also resulted in different time-to-market; air deliveries were 1.5 days faster than long distance trucking, while local truck deliveries and national air deliveries had a similar time-to-market (T-test; $p = 0.1$). Within direct supply chains, local/regional deliveries took the same amount of time as national deliveries. We attribute this to direct-to-consumer freight companies (e.g., Fed Ex and UPS) that have "next-day" freight service, which expands markets but comes with an added cost. Among both direct and intermediated supply chains, the mode of delivery (air vs ground delivery) had more bearing on time-to-market than the distance the product traveled.

We explored the ability of direct and intermediated supply chains to meet food safety regulations. These regulations include state Vibrio Control Plan requirements for post-harvest processing and requirements for maintaining product temperatures below 10 °C in the cold chain. Our hypothesis was that direct supply chains would have less opportunity for time and temperature abuse than intermediated supply chains because the time-to-market is faster and direct supply chains have fewer links than intermediated supply chains. Our findings agreed with this hypothesis; direct sales had lower rates of time and temperature abuse (8% of shipments) compared with intermediated supply chains (23% of shipments) (Table 3). The highest rates of time and temperature abuse were in intermediated supply chains shipped by air. Air freight companies do not guarantee refrigeration and recommend customers pack shipments to withstand 48 h (for domestic flights) or 72 h (for international flights) outside refrigeration, while all other stages of intermediated supply chains are refrigerated.

Using temperature sensor data, we modeled *V. parahaemolyticus* growth in supply chains. We had a similar hypothesis that direct supply chains would be safer because the time-to-market is faster. Somewhat counter-intuitively, *V. parahaemolyticus* die-off was greater in some intermediated supply chains than direct supply chains. The safest mode of shipment from a Vibrio risk perspective was long distance trucks delivering in intermediated supply chains, which had no (0/15) shipments with net *V. parahaemolyticus* growth. Long distance trucks are maintained at colder temperatures than other delivery modes (avg: 1.7 °C, data not shown) and have long delivery times (2.5 days, data not shown), which we suspect led to greater modeled *V. parahaemolyticus* die-off than other shipping methods. For more about V. *parahaemolyticus* modeling see (Love et al. 2018, 2019).

3.6. Traceability

We heard consistently that shellfish tags are the most important aspect of shellfish traceability. These tags are waterproof cards that travel with the product and list the address of harvester, harvest location, date of harvest, and other pertinent information. Tags are required by law to be stored at the final point of sale for 90 days. In addition to tags, there are many critical tracking events along the supply chains that trigger the collection of key data elements. Table 4 lists the information collected about products, the mode of storage, and what information is shared in the supply chain.

We found that producers collect much more data about their harvest than fit on a shellfish tag. Larger operations tend to track more variables with more technology (e.g., proprietary software vs by hand) than smaller operations. Fraud was a concern for some, which included manipulating or fabricating the information printed on the tag. For example, a participant referred to a past interaction with a producer (who was not in the study) who asked, "What date do you want me to put on the box?" Another producer reported knowing of other sellers writing new tags to manipulate the brand or harvest location.

Wholesalers play a key role in traceability. Large wholesalers assign lot numbers to incoming shipments and link these values to metadata about the package, sometimes using third-party software (e.g. Trace Register). Wholesalers in our study who have not transitioned to using lot numbers still maintain key data elements about a product in a digital log, such as in Excel (Microsoft, Redmond WA). In the simplest form, small wholesalers retain only paper invoices and a photocopy of the shellfish tag. One small wholesaler said "the reason is that the amount of effort needed to keep a log is more than we can do manually, and there is also a significant amount of investment needed to set up logs." For these smaller businesses, knowing the date a product shipped is the key piece of information needed to perform a recall and they are able to look them up in their files, if needed.

Freight carriers have invested heavily in logistics, with air cargo carriers and direct-to-consumer freight carriers operating online websites dedicated to product tracking. One airline representative noted that if the seafood industry used global positioning systems (GPS), "we

Table 4
Product recall and traceability in oyster supply chains.

Supply chain stage	Product recall (%) [a]	Practice recall (%)	Information retained about the product		Information shared with customers	
			Type	Format	Type	Format and delivery method
Producer	58	20	tag information [b]; harvest: broodstock, yield, location, amount per employee, air and water temp, amount culled; Vibrio log (in season); post-harvest: time/temp during processing, wet storage, refrigeration, at pick-up; lot number bill of lading;	digital spreadsheet; paper records; whiteboard	tag; packing slip; invoice; receipt; Vibrio records (in season); new customer paperwork [f]	tag; paper or digital documents; communicated by text message, phone, or email
Wholesaler	92	50	tag; invoice; receipt; bill of lading; date product arrives and departs warehouse; lot number or numeric code assigned by wholesaler.	tag; digital spreadsheet; paper records	tag; invoice; receipt; lot number; marketing materials [g]; new customer paperwork [f]	tag; paper or digital documents; sales force communicates by text message, phone call, or email
Freight Carrier	22	n/a	airbill [c]; bill of lading [d]; DTC tracking [e]; invoice; receipt	Paper logs; digital database	airbill; bill of lading; DTC tracking; invoice; receipt	Web-based tracking and e-alerts; paper and digital documents
Food Retail/ Restaurant	23	n/a	tag; invoice; receipt; packing slip; bill of lading; a product log maintained in-house	tag; digital spreadsheet paper logs	farm and/or brand name, harvest region, flavor profile, price	Menu, placards, sales pitch from front-of-house (for restaurant) or seafood counter (for food retail)

[a] Percent of participants that reporting ever being part of a product recall or conducting a practice recall in the past 12 months

[b] Shellfish tags in the United States contain the following information: a waterproof label with the shipper's name, address and certification number; harvest date; wet storage harvest date; ship date; harvest location; type of shellfish; quantity; original dealer's certification number. Reshippers are required to create a new tag, for example if they break down a box of oysters, and some wholesalers in our study were also reshippers. Tags must be kept by retailers and restaurants for 90 days after the final sale of the products.

[c] Airbill is a waybill created by an airline. Each shipment has a unique number that can be viewed in an online report by anybody with the airbill number. The report lists the number of packages, the weight, the time package was tendered, the estimated and actual arrival and departure times including intermediate stops, and the time the package was picked up by the customer.

[d] Bill of lading is a receipt of freight services commonly used by trucking companies. It is a document issued by the freight carrier, that lets the driver and carrier what products are being shipped, to where, and provides documentation of product delivery. Some bills of lading also report the temperature of the product at pickup and the temperature of the refrigerated truck.

[e] Direct to consumer (DTC) freight companies maintain similar online databases as airlines.

[f] Order and shipping schedules; proof of HACCP (or GFSI), audit, and insurance; certification information; credit check; farm or facility tour.

[g] Marketing material can include a flavor or taste profile, the geographic origin of the product, the growing region, or information about the producer.

could have every box traced to within 8 feet of where it exists at all time, however, there is a cost associated with that." The airline industry is considering switching to RFID chips for cargo to replace hand barcode scanning. Some trucking companies do use GPS to track their fleet, but not individual boxes.

Food retailers and restaurants use traceability information in a slightly different way than other stages of the supply chain. Chefs will use a mixture of traceability information, marketing materials, and their own knowledge (e.g., from visiting farms), and repackage this information into a narrative to educate sales staff and customers. As one chef put it, "Knowledge is what sells in the front of the house. They [waiters, bartenders] are not just order takers, they are sales people."

Among all stages of the supply chain, most respondents felt they were doing a good job with traceability. Some respondents were interested in upgrading traceability systems to use lot numbers. Some respondents were interested in digital tags, barcodes or QR codes, but others were disinterested in new technology. Reasons not to digitize tags include: current ability to track data efficiently, small operation size, concerns over computer failures leading to data loss, and, in one case, potential to increase time employees spend looking at their smartphones.

3.7. Product recalls

Many of the respondents we interviewed had participated in an oyster recall (Table 4). Washington State participants had more experience with recalls than Chesapeake Bay participants (63% WA vs 24% CB had ever participated in a recall). For example, 100% of Washington State producers had been involved in a product recall compared to just 17% of Chesapeake Bay producers. Nearly all wholesalers had participated in an oyster recall. All participants reported being able to track products one-up and one-down in supply chains, however, practice recalls were uncommon.

Since recalls were more common in Washington State, we posed additional questions to these participants. Many respondents agreed that recalls are important, however, there was frustration about the speed of recalls. Specifically, respondents felt that performing recalls 2–4 weeks after the product has sold is too slow. One wholesaler said, "By the time you find out there is a recall, the product is long gone and consumed." Another wholesaler said, "In the 20 recalls I have done, dating recalls back a month has only served to create a bunch of paperwork and headache for people. Most oysters don't last a month in a restaurant walk-in." A producer noted, "My biggest headache with recalls are the [mixed] oyster platters", which refers to restaurants that serve oysters from several farms on the same plate. Diseases linked to mixed oyster platters lead to multi-source recalls, which are more challenging to investigate than single-source recalls.

3.8. Regulations

Many respondents referred to food safety regulations in a positive light; they want to keep existing regulations because they feel the regulations do a good job. Producers had problems getting permits and could see benefits from streamlining the Army Corps of Engineers permitting process and softening environmental regulations. One producer wanted to simplify HACCP plans. One person noted that small producers sometimes cannot meet regulations, which results in problems for the entire industry. Wholesalers want to keep consumers safe, but some see redundancy in regulations and think communication about rule changes could be improved. Food retailers and restaurants want more guidance from agencies on HACCP plans and other requirements, instead of just enforcement. Some respondents, particularly restaurants, did not know enough about shellfish regulations to comment.

4. Discussion

4.1. General findings

Consumers, civil society, and governments are becoming more interested in where seafood is produced and where it goes once it is caught or harvested (Gephart et al., 2019; Northeast Fisheries Science Center, 2017). Oysters in the U.S. are marketed in a variety of ways, primarily via intermediated supply chains and to a lesser extent by direct supply chains. A producers' decision about which supply chains to use is based on the farm size and scale, price, logistics, and access to transportation hubs and markets. These decisions are also influenced by conduct within supply chains, which rely on relationships and trust (or lack of trust) between businesses, individuals' perceptions and expectations (e.g., what is expected of them and others, and expectations about product quality), and how well businesses listen and incorporate feedback from their customers. Oyster producers have a choice whether to outsource distribution and marketing to wholesalers, or to take over these functions in direct supply chains to perhaps capture additional revenue (Chase, Otts, 2016; Johnson, 2018; Stoll et al., 2015). Intermediated supply chains, by their definition have more connections, and we found this introduces a longer time-to-market and a higher incidence of time and temperature abuse. However, these factors did not lead to greater modeled *V. parahaemolyticus* risks. While our work focused on the conduct and performance of U.S. supply chains for a luxury seafood product, the findings can have parallels to supply chains for other fresh or live seafood products.

4.2. Food safety and traceability

Food safety regulations have been the catalyst for establishing many of the traceability requirements in seafood (Lewis, Boyle, 2017). One flashpoint for food safety and traceability of molluscan shellfish are Vibrio bacteria, which are naturally occurring microorganisms that accumulate in molluscan shellfish and cause disease in humans (Newton et al., 2012; NSSP, 2015). There are several reasons for the focus on Vibrios. There is growing consumer demand for raw oysters sold to the half-shell market, oysters are a riskier food item, and there is growing seasonal demand for summer oysters. Oysters grown in warmer water temperatures correlate with increased Vibrio risks (Shapiro et al., 1998). Climate change is also increasing the geographic range that Vibrios flourish (Baker-Austin et al., 2017; Deeb et al., 2018), as evidenced by an unexpected outbreak of *V. parahaemolyticus*-caused gastroenteritis from Alaskan oysters (McLaughlin et al., 2005). Shellfish producers in our study engage in national and international commerce, which can complicate traceback and product recalls, and while digital traceability technology has been developed and piloted in some regions, it has not been widely adopted (Miller et al., 2014).

Traceability is critical during a product recall, and poor handling of recalls has health and economic implications. Studies about recalls have found media coverage can hurt the reputation of a business or industry and have a negative economic impact that continues well after the product is recalled (Peake et al., 2014; Taylor et al., 2016). In our study, several businesses were concerned that oyster products implicated in recalls could be consumed week(s) before a notice came to return or destroy them, and businesses were not satisfied with the delay in state health departments issuing recalls. Aligning expectations between state health departments and the industry seems to be needed, and regulators could do a better job communicating with the industry about the challenges of conducting rapid recalls. However, in general, businesses were satisfied with food safety regulations, agreed they were important to keep customers safe, and have suggestions to streamline policies.

We explored whether shellfish safety is affected by the configuration of supply chains and found that direct supply chains, which are shorter

than intermediated supply chains, had fewer incidences of time and temperature abuse. Translating this into practical advice for the industry could mean including TTIs or temperature data loggers in shipments to monitor product temperature, especially when shipping to new destinations, via longer supply chains, or by methods like air freight that do not provide refrigeration. Reducing high temperature abuse during harvest and post-harvest processing is another key period to control bacterial growth (Love et al., 2018; NSSP, 2015).

4.3. Food quality and marketing

High value foods, including oysters, require a special focus on product quality and the unique attributes (e.g., origin, growing methods, salinity, etc.) that contribute to value (King, Venturini, 2005). There was agreement among producers and retailers on quality and key product attributes, however, more could be done to align expectations. Opportunities to stimulate these conversations include farm tours, tasting panels, and industry sponsored meet-ups (Cochet et al., 2015). Some participants in the study market their products specifically linking geographic origin with taste, similar to *terrior* for wines, while others do not. The oyster aquaculture industry could do more to help businesses tell the story behind their products including any social, economic, or ecological benefits their product provides. Willingness-to-pay studies (Acquah, Petrolia, 2014) and studies of consumer preferences can also help develop marketing materials and retail strategies to target consumers (Kecinski et al., 2017; Lawley, Birch, 2016). Additionally, researchers should continue exploring aquaculture's role in local, regional, national, and international food systems.

4.4. Relationships within supply chains

Businesses that cooperate and work synergistically with supply chain partners can reduce food quality and safety risks and waste (Gobel et al., 2015; Wang et al., 2015). We found the seafood industry places a high value on trust and personal relationships, which develop over time and require consistency (e.g., in product quality, inventory, and on-time deliveries). Correcting information asymmetry, setting realistic expectations, and meeting those expectations are all important for building relationships. In some cases there was some mistrust among businesses and some concerns over power dynamics, such as a seller not feeling able to voice concerns about issues for fear of losing customers. In other instances we observed coordination between businesses to optimize value (Jespersen et al., 2014; Stevenson et al., 2016). Sterling and colleagues define these relationships as “fragmented value chains” where buyers and sellers are suspicious of each other, “co-operative value chains” where businesses cultivate positive working relationships, or “collaborative value chains” where businesses develop shared long-term strategic alignment (Sterling et al., 2015). Future studies could stratify their sampling by the relationships within value or supply chains.

4.5. Limitations

There were several limitations to our study. The recruitment was based on chain sampling methods and therefore the findings may not be representative of the entire Chesapeake Bay or Washington State oyster aquaculture industry. We were not able to map the geographic relationship among groups, as others have done for small-scale fisheries (Kittinger et al., 2015), because of concerns over confidentiality. Respondents and industry representatives were not interested in sharing the types of economic data needed for a supply chain analysis, therefore future work in this area would be beneficial to supplement existing studies on farm gate price and economic impact in the study regions (Hudson, 2017; Northern Economics Inc., 2013).

5. Conclusions

There are several conclusions from the study. First, supply chain configuration, performance, and conduct are essential elements when assessing food safety and quality. Many studies only consider the final product and not the path that the product travels to reach a market nor how businesses interact within the supply chain. Taking a supply chain perspective provides a different lens with which to view this issue. Second, using a mixed-methods study design that included asking participants about their beliefs, experiences, and perceptions yielded a rich and nuanced context and contributed to the overall analysis. Lastly, this paper makes several contributions. We found that supply chain configuration affects performance, for example, direct supply chains had fewer incidences of time and temperature abuse than intermediated supply chains. We also explored how businesses perceive product quality, documented different approaches to traceability and information sharing; and explored attitudes and perceptions about food recalls.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the Washington State and Chesapeake Bay oyster aquaculture industry and those individuals and businesses that participated in the study. This research was primarily supported by the NOAA Saltonstall-Kennedy Grant Program (16GAR008). Some materials and other study expenses were supported by the Johns Hopkins Center for a Livable Future with a gift from the Greater Kansas City Community Foundation. We also thank the peer reviewers for their time and input.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2019.734569.

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