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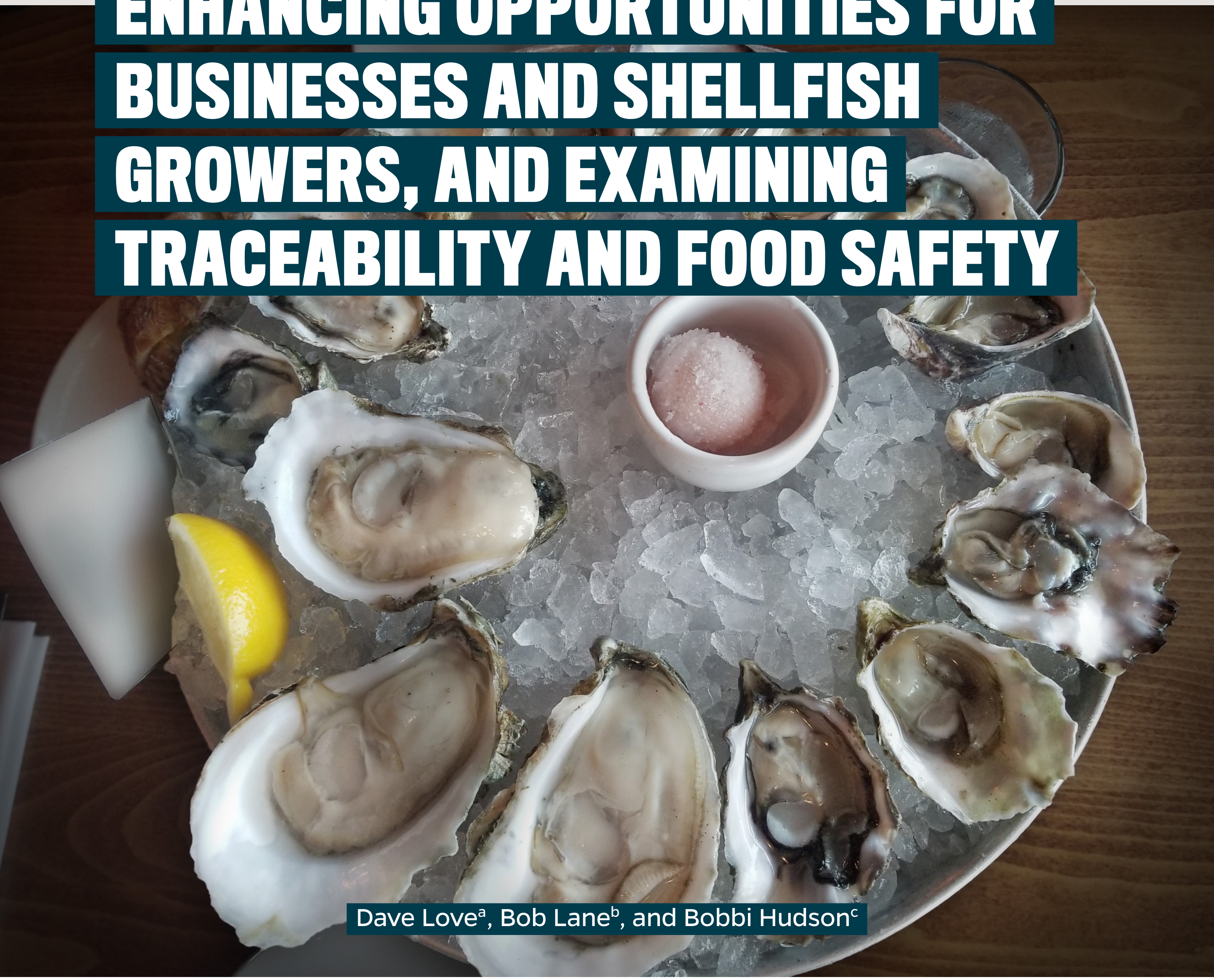
SUPPLY CHAINS FOR AQUACULTURED OYSTERS: ENHANCING OPPORTUNITIES FOR BUSINESSES AND SHELLFISH GROWERS, AND EXAMINING TRACEABILITY AND FOOD SAFETY



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Executive Summary

Oysters are experiencing a renaissance in the United States and many dozens of varieties are available at raw bars and restaurants across the country. Historically, raw oysters were a seasonal treat, only available in the fall and winter when the likelihood of spoilage was low. Thanks to a thriving aquaculture industry, there is now a year-round supply of raw oysters sold by wholesalers with regional and national distribution networks. With this growing trend of summer raw oyster consumption, the starting point for our research was the question: Is it safe to ship raw oysters in the summer?

Shellfish safety has always been an important issue for the industry, regulators, restaurants and consumers. Research and policy have mainly focused on two key periods, harvest and post-harvest processing, to reduce *Vibrio* risks. Eating raw or undercooked shellfish is a risk factor for developing vibriosis, a diseases caused by *Vibrio* bacteria [1]. These bacteria flourish in warm summer months, and warming waters caused by climate change are increasing both the geographic spread of these bacteria and cases of vibriosis [2, 3].

Little is known about supply chains and their critical role in keeping shellfish safe during distribution, and so we spent two years working with Chesapeake Bay and Washington oyster industries and their supply chains, tracking 125 boxes of oysters on their journey from dock to plate.

Raw oysters have about a week to 14-day shelf-life (depending upon whom you ask), so there is a strong incentive to move products quickly. We found oyster shipments are delivered to retailers between one to five days after harvest, depending upon the type of supply chain and method of transportation.

We placed coin-sized temperature sensors inside oysters and found that as they moved down the supply chain (towards consumers), the oysters became colder and there was less variation in temperature. The average temperature of oysters in the supply chains we studied was 39°F, which is 11°F below the maximum allowable temperature (50 °F). However, the outliers (both high and low temperature abuse) are more interesting, because these can cause problems for product quality and safety. We found that nearly a fifth of shipments went above the regulated temperature criteria for an hour or more, and the average amount of time these boxes of oysters spent out of temperature compliance was 2.5 hours. The maximum temperature any oyster reached in our study was 58°F.

Using the time and temperature data we collected and model equations for Vibrio growth rates and risk, we asked if temperature abuse leads to bacterial growth and health risks. We found that most shipments had lower levels of modeled *Vibrio parahaemolyticus* (and lower disease risks) at retail than at harvest. This means that most supply chains were making oysters safer to eat rather than riskier. In a few cases we found *V. parahaemolyticus* growth, which was caused by a failure to cool oysters quickly after harvest or breakdowns in refrigeration in the supply chain.

A producers' choice of supply chains can affect product quality and safety. Supply chains that have more connections are also more vulnerable to time and temperature abuse, and some modes of delivery are inherently riskier than others. As our food supply becomes more global, safety in handling and distribution of foods becomes critical. While it appears that U.S. shellfish supply chains are working well and maintain shellfish quality and safety, there is room for improvement at each stage of the supply chain, in how products are handled and how businesses interact with each other to maintain the value, safety, and quality of the product.

Purpose

Seafood is made available to consumers via a complex supply chain of producers, processors, importers, wholesalers, distributors, and retailers. Supply chains support the flow of products, information, and money. Intermediated supply chains can increase food quantity and availability by connecting distant producers with consumers, but there are many challenges in maintaining product quality and product information that supports traceability through these long supply chains. An example of a breakdown in product information and traceability would be selling illegal, unreported, and unregulated (IUU) seafood, which has become a major concern in the United States and globally. An example of a breakdown in product quality is inadequate temperature control through the supply chain, which can lead to spoilage and potentially foodborne illnesses. Improving the way supply chains operate with respect to product flows and information flows can allow regulators to track products and minimize food safety risks, businesses to hold each other accountable and reduce economic risks, and consumers to differentiate among products in the marketplace and track changes in industry sustainability.

Direct supply chains have fewer steps between producers and consumers than intermediated supply chains, and often represent pathways for products to be sold locally or regionally. An example of a direct supply chain is a shellfish grower who sells at a farmers market or to a local restaurant. Similar challenges exist in maintaining a cold chain from dock to plate, and different but important traceability challenges, such as moving from paper to digital record keeping. Direct supply chains can empower farmers to claim more money for their product, in part by retaining valuable information about their products like *locally-caught* or the use of sustainable methods or fishing gear. Aquacultured oysters are now being marketed like wine, by highlighting growing region as selling points.

NOAA's Marine Aquaculture Policy acknowledges a "*growing consumer demand for safe, local, and sustainably produced seafood… and growing interest in maintaining working waterfronts*". We see supply chains as a critical ingredient for creating a food system that connects producers with consumers and creates economic opportunities for businesses and shellfish growers. The challenge is that seafood supply chains are complex and relatively unstudied.

In this study, we investigated aquacultured shellfish supply chains because they are one of the most valuable domestic aquaculture products, representing 20% of total domestic aquaculture value. Within shellfish, we narrowed the scope of work by selecting one product group, aquacultured oysters, and two case study locations: Virginia and Maryland (e.g., Chesapeake Bay) and Washington State (e.g., Puget Sound and Pacific Coast). We selected aquacultured oysters because they are commonly eaten raw, posing a greater food safety risk than clams or mussels, and oysters constitute over half of farmed shellfish value. Washington State and Virginia are No. 1 and No. 2 in aquacultured oyster sales and combined have nearly a third of all oyster farms and over half of all oyster sales. We include Maryland because it has a burgeoning shellfish aquaculture program and contributes to production coming from the Chesapeake Bay region. Massachusetts, also a leader in shellfish production, was not included in the study due to resource and time constraints.

Diseases associated with consuming raw or undercooked products are a major concern for the shellfish industry. As molluscan shellfish production and consumption increases, the number of *Vibrio* infections from molluscan shellfish is also increasing. *Vibrio vulnificus* and *V. parahaemolyticus* are gram-negative bacteria naturally found in estuarine and marine environments. From 1996 to 2010, infections associated with *Vibrio*-contaminated seafood, including oysters, tripled and there was also a 32% increase in illnesses from *Vibrio* spp. infections in 2013 compared to 2010-2012. Good temperature control of molluscan shellfish from harvest throughout the distribution process is essential to reducing microbial growth and improving food safety and quality. By studying the performance of aquacultured oyster supply chains, product traceability, and temperature control we can have direct impacts for the shellfish aquaculture industry.

Goal

To enhance opportunities for businesses and shellfish growers by better understanding how aquacultured oysters move from producers to consumers through supply chains, and to improve product traceability and food safety.

Objectives

1. Conduct qualitative, interview-based case studies of six different oyster supply chains: direct-market; intermediated supply chains; and mainstream supply chains for oysters produced in Virginia and Maryland (Chesapeake Bay) and Washington State (Puget Sound, Pacific Coast).

2. Conduct quantitative, field-based studies of oyster temperature throughout distribution in six different oyster supply chains: direct-market; intermediated supply chains; and mainstream supply chains for oysters produced in Virginia and Maryland (Chesapeake Bay) and Washington State (Puget Sound, Pacific Coast).

3. Synthesize and integrate supply chain results and develop recommendations to improve food safety.

Approach

Study design. Our general approach was modeled after work by King and colleagues [4] and influenced by food systems methodology [5]. We employed a mixed-methods study with two components: i) interviews of oyster supply chain businesses to better understand their views and perceptions (ie., Objective 1); 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 (ie., Objective 2).

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 (Figure 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.

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. (See Appendix for survey tool)

Oyster temperature tracking. Temperature sensors (Smart Buttons, ACR Systems Inc., British Columbia, Canada) were used to track oyster temperature and ambient air temperature at 1 min or 10 min time intervals starting at harvest and through the supply chain. The manufacturer reported that the sensors have a working range of -40 °F to 185 °F, which is within the range of temperatures we expected to observe in our cold chains. The reported accuracy of the sensors was ± 1.8 °F from -22 °F to 113 °F. We independently tested the inter-button variability in our laboratory using simulated field conditions and determined it was ± 1 °F. We employed a pilot study with wholesalers to determine the variability among three oyster boxes shipped to the same final destination, and determined that a single box was adequate to make generalizations about temperatures in warehouses and trucks (Appendix Figure A4). Hand-held analog thermometers, calibrated in an ice water bath, were used for spot readings on farms.



We visited oyster aquaculture operations to monitor the harvest and on-farm processing. The temperatures of the harvest water, ambient air, wash water, and the walk-in refrigerator were measured. Notes were also taken about sun exposure and processing methods. After oysters were harvested and unloaded at the dock, Smart Button sensors were inserted into oysters to measure temperature at 1 min intervals during washing, grading, boxing and storage.

All oysters containing temperature sensors were wrapped in red duct tape to prevent their introduction into the food supply. Just before the product was shipped, the sensors reading at 1 min intervals were removed and new sensors reading at 10 min intervals were inserted inside one oyster per 100-count box. (Sensors set at 10-minute intervals increased sensor operating life up to two weeks.) Farms that sell products in mesh bags were asked to place the bags inside a box. One Smart Button sensor was taped to the outside of each 100-count wax box to measure ambient air temperature in shipments. Between four and eight boxes were tracked from each farm. Stamped envelopes, a study description, and a notecard to record arrival times were enclosed in each box to allow the final recipient (food retail or restaurant) to return the sensors to the Virginia Seafood Agricultural Research and Extension Center at Virginia Tech. Producers were offered financial compensation for boxes of oysters used in the study.

Vibrio modeling. We modeled the expected abundance of *V. parahaemolyticus* in oysters and the associated risk of gastroenteritis using internal oyster temperature data. Statistical models were based on the U.S. Food and Drug Administration's risk assessment of *V. parahaemolyticus* in raw oysters [6]. The models first estimated the abundance of bacteria at the point of harvest and determined bacterial growth rate when exposed to temperatures higher than a refrigeration threshold of 41.7 °F (5.4 °C) as well as bacterial die-off rate when stored at or below the refrigeration threshold. *V. parahaemolyticus* abundance estimation was modeled iteratively, such that the previous estimation informed future abundance, whereas the calculation of risk was based upon the level of bacteria at a given time point. The abundance at the point of harvest was estimated as a function of harvest water temperature using the following equation:

$$V = -0.63 * 0.1W$$

Where V is the base-10 log-transformed number of *V. parahaemolyticus* bacteria per gram of oyster meat (Vp/g) at the time of harvest, and W is surface water temperature (°C) measured at the time of harvest. *Vibrio* abundance post-harvest was calculated using a growth/die-off model, which can be expressed as follows:

$$A_i = \begin{cases} A_{i-1} + 0.00372(T_i - 5.4) & \text{if } T_i \geq 5.4\ °\text{C} \\ A_{i-1} - 0.0003 & \text{if } T_i < 5.4\ °\text{C} \end{cases}$$

where A_i is the base-10 log-transformed Vp/g at time point i, A_{i-1} is abundance at the previous time point (10 minutes prior) and its value at the point of harvest is V, and T is the ambient air temperature (°C) measured at time point i. Risk was calculated at each time point using a Beta-Poisson dose-response model, which can be expressed as:

$$R_i = 1x10^{-5} * \left(1 - \left(1 + \frac{D_i}{3.54x10^7}\right)^{-0.6}\right)$$

where R_i is the expected number of gastroenteritis cases per 100,000 servings of one dozen oysters, and D_i is the dose of pathogenic *V. parahaemolyticus* that is estimated using the following equation:

$$D_i = 36 * 10^{A_i}$$

Given that the observable doses only occurred on the linear portion of the estimated Beta-Poisson slope, a linear version of the model was approximated using Taylor series:

$$R_i = 1x10^{-5}\left(\frac{0.6}{3.54x10^7}\right) * 36 * 10^{A_i} = 0.0061 * 10^{A_i}$$

For all modeling efforts, air temperature at the time of harvest was held constant in the model until sensors were placed in oysters; water temperature at harvest was substituted if air temperature was not measured. All modeling was performed in R statistical software version 3.4.3 [7].

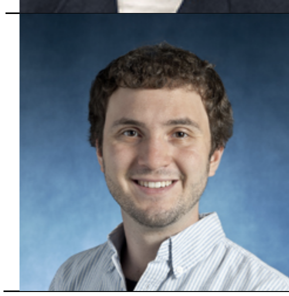
Qualitative data analyses. Notes were taken during each interview and shared with interviewees to check for accuracy. Descriptions of interviewee responses were entered into a spreadsheet in Excel (Microsoft Corp., Redmond, Washington) that was used for data management and analysis. A member of the study 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.

Statistical analyses. Temperature sensor data were downloaded using manufacturer software (Trend Reader, ACR Systems Inc., British Columbia, Canada), analyzed in Excel (Microsoft, Redmond, WA) and graphed in Prism (v6, GraphPad, La Jolla, CA). One-way ANOVAs with repeated measures and Greenhouse Geisser corrections were used to compare the mean temperature among groups. Shipments with incomplete data were removed from the one-way ANOVAs. If significance was observed in an ANOVA then Tukey's multiple comparison test was used with individual variances computed for each comparison. T-tests were used to compare mean temperatures by step of supply chain in VCP months versus a non-VCP months.

To better understand temperature outliers, we classified each shipment by the number of times temperature sensor values exceeded certain National Shellfish Sanitation Program (NSSP) criteria. These criteria were oysters with internal temperatures > 50 °F or a shipping environment > 45 °F. We also added another criterium for cold abuse, oysters or their environment held at < 35 °F. This is not part of the NSSP, however, oysters held below 35 °F are susceptible to gaping. We noted if shipments were above or below the criteria for 1 hr or more (based on readings taken at 10 min intervals).

Project Team

	Individual, Title	Roles and Responsibilities
	**Dr. Dave Love** Assoc Scientist, Johns Hopkins University (JHU), Center for a Livable Future (CLF)	Principal Investigator. Dave led the project, trained students, attended most site visits, reviewed and assisted with qualitative and temperature methods development, assisted with recruitment, led portions of the temperature data analysis, and lead manuscript and final report writing.
	**Robert (Bob) Lane**, VT, Extension Specialist, Virginia Seafood AREC	Co-Principal Investigator Bob led Objective 2 related to temperature monitoring, assisted with recruitment, attended most site visits, maintained and downloaded data from temperature sensors, cleaned temperature sensor data, assisted with temperature data analysis, reviewed manuscripts and the final report, and led the writing of the Virginia Cooperative Extension factsheet.
	**Bobbi Hudson**, Pacific Shellfish Institute, Executive Director	Co-Principal Investigator. Bobbi advised on project activities related to Washington State shellfish aquaculture (Objectives 1 and 2), assisted with recruitment, reviewed and edited manuscripts and the final report, and led the to Washington state communication activities including several conference presentations and writing a newsletter. (Objective 3).
	**Dr. Jillian Fry**, Assistant Professor Towson University	Project investigator. Jillian was based at JHU until Summer 2019. She assist in developing case study questionnaires and case study design and assist in training Lillian and Aditi in qualitative methods, and data analysis (Objective 1). Jillian reviewed and edited manuscripts.

	**Jamie Harding**, GIS Specialist, JHU, CLF Maryland Food System Map	Project investigator. Jamie lead the mapping of supply chains (Objectives 1 and 2), and reviewed manuscripts.
	**Lillian Kuehl**, masters student research assistant, Western Washington University	Lillian assisted with recruitment, in case study interviews, and temperature sensor experiments in Washington State in year 2 (Objectives 1 and 2).
Aditi Mittal, masters student research assistant, JHU		Aditi assisted in case study interviews and temperature sensor experiments in Chesapeake Bay in year 1 (Objectives 1 and 2).
	**Kate Clancy**, Visiting Scholar JHU CLF	Kate advised on project methods and approach, qualitative data tools, and reviewed study data and manuscripts. Kate was paid by a different source of funding than NOAA SK.
	**Ben Davis,** postdoc, JHU	Ben performed the Vibrio risk modeling using temperature sensor data. Ben was paid by a different source of funding than NOAA SK.

Findings

Objective 1

Qualitative Interviews [8]

<u>Qualitative study participants</u>. The study population was 143 businesses that participated in the Washington State and Chesapeake Bay oyster supply chain study representing six different types of supply chains (Figure 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).

<u>Supply chain structure</u>. We asked a series of questions about the structure and size of these supply chains (summarized in Table 1, Figure 2, and Supporting Information Figure 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., 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.

<u>Roles, expectations, and interactions among businesses</u>. A clear understanding of the roles, expectations, and preferences among members of the cold chain is critical for maintaining food 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 [9]. 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 hours for domestic trips and 72 hours for international trips [10-12]. 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.

Perceptions of product quality attributes. Intermediated supply chains have three to seven businesses involved in bringing products to market (Figure 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.

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
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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 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.

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 to 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.

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.

Objective 2

Temperature Sensor Study [8, 13, 14]

Oyster temperature study population. Throughout the two-year study, producers shipped 125 boxes or bags of oysters to customers in 20 states, Washington D.C., and Hong Kong, China (Table 5). Eighty-one percent of the temperature sensors were returned with usable data, and the return rates were similar for Washington State and Chesapeake Bay supply chains. Roughly equal numbers of shipments were made with Chesapeake Bay oysters as were made with Washington State oysters, however, the Washington State portion of the study had twice the number of participants. This was due to a change in the study methodology in Washington (as mentioned in section 2.1) to include more national and international shipments.

Figure 3 provides a map of the origin and final destination of shipments in this study. Participants were geographically dispersed and included 13 oyster producers from three states, 38 seafood wholesalers from 16 states, 63 grocery stores, seafood markets, and restaurants from 17 states, and 27 freight carriers, including 7 commercial airlines and 11 commercial trucking companies, that serviced markets ranging from local to international.

Summary of oyster cold chains. In Figure 4 we provide a heat map indicating the average internal oyster temperature for each shipment at each stage of the supply chain. Overall, oysters were maintained at an average temperature of 4.4 ± 2.7 °C (40 ± 5 °F) among all participants. Oysters harvested from the Chesapeake Bay were maintained 1.2 °C (2 °F) warmer in supply chains than oysters originating from Washington State (Figure 5; see Table A.1 for means and p-values). These differences were primarily due to warmer oyster temperatures among Chesapeake Bay producers (3.4 °C warmer) and freight carriers (0.9 °C warmer) compared to Washington State producers and freight carriers (Figure 5). There were no significant differences in oyster temperatures between wholesalers, food retailers, or restaurants who handled Washington State and Chesapeake Bay oysters.

Chesapeake Bay oyster cold chains. We visited six farms during VCP months and collected interview and temperature data related to harvest and on-farm processing (Tables 5, 6, and 7, Figure 7). On average, the harvest water temperature was 73.2 °F ± 4.0 °F (range: 70 °F to 80 °F) and the air temperature at harvest was 70.3 °F ± 1.5 °F (range: 68 °F to 72 °F). Processing steps were similar among the producers and involved different combinations of washing, grading, hand-sorting, boxing and mechanical refrigeration.

Figure 6 presents annotated temperature profiles for each of the six producers during VCP months of June - September. Several details are important to note in Figure 6. Figure 6A and 6B are harvests that occurred on the same day at one farm—the first, a large morning harvest and the second, a smaller harvest to fulfill last minute orders. Figure 6C has a notable point of inflection in temperature when box lids were added during refrigeration that slowed product cooling, which produces a similar insulating effect as putting a lid on a cup of hot coffee. The producer in 6C appeared to have an undersized refrigerator chiller, which also increased the time to cool the product. Producers in Figure 6D and 6G processed oysters the day before shipment. In Figure 6E, the producer washed and refrigerated the product immediately after harvesting, and then later re-washed the product with 60 °F tap water, which created a temperature spike. In Figure 6F, the producer used liberal amounts of ice at every stage of processing and achieved rapid, staged cooling.

Chesapeake Bay oyster temperature by stage of supply chain. Oysters entered the supply chain warmer in VCP months than a non-VCP month, however, the final oyster temperature at the retail level of the supply chain was the same (Appendix text and Table A4). After determining that VCP was a significant factor, we pooled the temperature sensor data by VCP status and by stage of supply chain (Figure 7).

We hypothesized that internal oyster temperatures would decrease as the product moved through the cold chain, a concept that agrees with self-reported cold chain temperatures in Table 1. In the non-VCP month, there was no significant difference in internal oyster temperature comparing all supply chain groups (producers, freight carriers, wholesale, wholesale delivery, food retailers/restaurants) (ANOVA: $F = 2.4$, $p = 0.18$). There was a significant difference in the box temperature among all groups (ANOVA: $F = 6.1$, $p = 0.03$), but these differences were not statistically significant when comparing neighboring groups, such as producers to freight carriers, freight carriers to wholesalers, or wholesalers to food retailers/restaurants.

In VCP months, there were significant differences in both the internal oyster temperature (ANOVA: $F = 76.4$, $p < 0.0001$) and the box temperature (ANOVA: $F = 38.8$, $p < 0.0001$). Pairwise comparisons suggest that producers, when holding product under temperature control, maintain boxes at cooler temperatures than freight carriers ($p < 0.05$), but producers and freight carriers had similar internal oyster temperatures. Freight carriers maintained boxes at warmer temperatures than wholesalers ($p < 0.0001$), which led to warmer internal oyster temperatures ($p < 0.0001$). Box temperatures were not different between wholesale and wholesale delivery or between wholesale delivery and food retailers/restaurants, suggesting that a relatively uniform environmental temperature was maintained along this portion of the supply chain. Internal oyster temperatures were cooler in wholesale delivery than wholesale ($p < 0.01$), perhaps due to the use of ice during delivery. There was no difference between internal oyster temperatures during wholesale delivery and at food retailers/restaurants. (See Appendix Table A5 for p-values from all tests.)

*Chesapeake Bay outlier analysis***.** In addition to comparing mean values, it is also useful to analyze outliers when the temperature was warmer or colder than expected for sustained periods of time. Overall, 19% (7 of 36) of shipments had internal oyster temperatures greater than 50 °F for more than 1 hr (all were in VCP months). The product temperature in these seven shipments exceeded NSSP criteria; the maximum internal oyster temperatures were: 50.9 °F (for four shipments), 52.7 °F, and 54.5 °F. Over four-fifths of shipments (81%; 21 of 26) in VCP months were held in storage conditions above 45 °F for over 1 hr.

The internal oyster temperature was less than 35 °F for more than 1 hr in 28% (10 of 36) shipments, which puts products at risk for freezing and was more common in a non-VCP month than in VCP months.

*Chesapeake Bay exemplar temperature profiles***.** We plotted temperature profiles of six shipments to show typical examples of temperature control issues (Figure 8). Figure 8A depicts a 100-count waxed box shipped in March 2017. The box was iced by the producer just before freight carrier pick-up and the product remained at near freezing temperatures for ~ 24 hours, which could kill oysters or reduce shelf life (we did not visually inspect the box for gaping or mortalities). Figure 8B shows a 50-count box of oysters shipped direct to a consumer in July 2017. The packaging was a polystyrene cooler containing gel packs nested inside a cardboard box. The box was shipped using a national commercial freight carrier with 2-day ground delivery. The product temperature slowly climbed from the mid-30s °F to the low-40s °F during shipment, but remained well below 50 °F, indicating that 2-day shipment under these circumstances was acceptable. Figure 8C and 8D show short and long periods of time when 100-count boxes of oysters were outside of temperature control. The internal oyster temperature slowly rose and then fell once temperature control was recovered by the wholesaler. Figure 4D is one of five shipments where internal oyster temperatures exceeded 50 °F for more than 1 hr (as described above). We suspect that these issues could be due to the product being stored on a loading dock between trips in a refrigerated truck. Figure 8E depicts a spike in temperature during delivery of a 100-count box of oysters to a food retailer/restaurant in March 2017. The product temperature stabilized after the box was moved to the walk-in refrigerator. Figure 8F was more severe, and shows a food retailer/restaurant in June 2017 whose refrigerator was either malfunctioning or set at an unsafe temperature for storage of shellfish.

Washington State oyster cold chains. Post-harvest cooling is a critical period to control the growth of *V. paraehemolyticus.* Washington State producers cooled oysters to an average temperature of 3.2 ± 2.3 °C (38 ± 4 °F) (Table A.1), and most farms achieved temperatures below 10 °C (50 °F) in three hours or less (Figure 9). Once oysters left the farm they remained at a similar temperature across the remaining stages of the supply chain (ANOVA, $p = 0.1$).

Among freight deliveries, long-distance ground freight carriers (i.e., truck shipments greater than 24 hours) maintained oysters at 1.6 ± 1.3 °C (35 ± 2 °F), which was significantly cooler than other forms of freight [freight forwarders (4.4 ± 3.3 °C; 40 ± 6 °F; $p = 0.04$), local ground freight carriers (4.2 ± 2.8°C; 40 ± 5 °F; $p = 0.009$), or air freight carriers (5.5 ± 2.7 °C; 42 ± 5 °F; $p = 0.001$) (Figure A.1)]. Oysters were warmer when freight carriers shipped in months with Vibrio Control Plans (VCPs) compared to a non-VCP month (t-test, $p = 0.008$, Figure A.2). Among direct to consumer freight deliveries, one-day deliveries provide cooler oysters than two-day deliveries, however, even one-day deliveries can approach 10 °C (50 °F) if the receiver is located in a hot climate (Figure A.3).

Washington State and Chesapeake Bay oyster shipments with high temperatures. Over the two year study, 18% of all shipments (16/91) and 16% of domestic shipments (14/89) exceeded 10 °C (50 °F) for one hour or more (Figure 10a, Table A.2). The median amount of time these 16 shipments spent above 10 °C (50 °F) was 2.5 hours (range: 1.3 to 62 hours). The highest internal oyster temperature recorded in the study was 14.4 °C (58 °F). Washington State and Chesapeake Bay supply chains had similar rates of shipments over 10 °C.

Supply chain groups had the following rates of oyster shipments over 10 °C: freight carriers (7%), wholesalers (6%), producers (4%), and food retail/restaurants (2%). Freight carriers were higher than other groups mainly due to the higher rates of oysters over 10 °C that were shipped by air freight (35%) (Table A.2).

We reanalyzed the oyster temperature data by supply chain (direct vs intermediated). 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).

Washington State and Chesapeake Bay oyster shipments with low temperatures. Oysters can be at risk for freezing in cold chains. Roughly half of all shipments (48/91) had oyster temperature readings below 1.67 °C (35 °F) for one hour or more (Figure 10b, Table A.3). The coldest internal oyster temperature recorded in the study was -2.2 °C (28 °F). Rates of near freezing were similar across all supply chain groups (Table A.3). Oyster shipments in the Washington State supply chains were often colder than oyster shipments in the Chesapeake Bay supply chains (Figure 2, Table A.3).

Overall supply chain performance. We 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. 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.

Modeling *V. parahaemolyticus* abundance and health risks. Models of *V. parahaemolyticus* abundance and associated risks are presented for Washington State shipments (Figure 11). The model found a net decrease in *V. parahaemolyticus* abundance throughout the supply chain (from harvest to food retail/restaurant) in 82% (41/50) of Washington State shipments. The highest modeled *V. parahaemolyticus* concentration in Washington State was 1,135 *V. parahaemolyticus* per gram of oyster tissues, which corresponded to an illness rate of 0.84 per 100,000 servings.

In the Chesapeake Bay study, 66% (27/41) of shipments had a net decrease in *V. parahaemolyticus* abundance in the supply chain. The highest modeled *V. parahaemolyticus* concentration in the Chesapeake Bay was 115 *V. parahaemolyticus* per gram of oyster tissue or an illness rate of 0.07 per 100,000 servings (Figure 12). (We assumed a serving to be 12 raw oysters.). Overall, from both regions, 75% (68/91) of shipments had a net decrease in *V. parahaemolyticus* abundance in the supply chain.

Figure 13 provides the percent change in *V. parahaemolyticus* abundance for shipments originating from Washington State and Chesapeake Bay, comparing the modeled *V. parahaemolyticus* concentrations at harvest to the modeled *V. parahaemolyticus* concentrations at the end of the supply chain.

We reanalyzed the data by type of supply chain. Our hypothesis was 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.

Objective 3

Synthesis and Recommendations [8, 13]

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 [15, 16]. 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 [17-19]. 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.

Relationships within supply chains. Businesses that cooperate and work synergistically with supply chain partners can reduce food quality and safety risks and waste [20, 21]. 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 [22, 23]. Sterling and colleagues define these relationships as "fragmented value chains" where buyers and sellers are suspicious of each other, "cooperative value chains" where businesses cultivate positive working relationships, or "collaborative value chains" where businesses develop shared long-term strategic alignment [24].

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 [25]. 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 [26]. 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 [27] and studies of consumer preferences can also help develop marketing materials and retail strategies to target consumers [28, 29].

Food safety and traceability. Food safety regulations have been the catalyst for establishing many of the traceability requirements in seafood [30]. 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 [9, 31]. 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 [32]. Climate change is also increasing the geographic range that Vibrios flourish [2, 3], as evidenced by an unexpected outbreak of *V. parahaemolyticus*-caused gastroenteritis from Alaskan oysters [33]. 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 [34].

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 [35, 36]. 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.

Time and temperature abuse. Temperature control of shellfish during harvest, post-harvest processing, and throughout the distribution chain is essential to control Vibrio growth [37, 38]. On average, businesses in our study maintained oysters about 6 °C (11 °F) cooler than the 10 °C (50 °F) guidance criterium established by the U.S. government [9], however, temperature spikes occurred in some shipments. Temperature sensors indicated that nearly one in five oyster shipments exceeded 10 °C for an hour or more, and the median time spent out of temperature control was 2.5 hours. Temperature exceedance rates were similar between Washington State and Chesapeake Bay cold chains, suggesting that there is internal validity to this finding. A similar study in Australia found that 47% of shipments (21/45 shipments) were held above 10 °C [39], which is more than twice the percentage found in the U.S.

Temperature control issues come in many different forms: from faulty mechanical refrigeration units, delays in transit or in unloading cargo at airport runways, leaving products on docks or loading docks for too long, or forgetting to refrigerate boxes upon arrival at restaurants. Two businesses in our study routinely had problems maintaining oyster temperatures and accounted for a third of all temperature exceedances in the study. These outliers, however, cannot be brushed aside. Temperature abuse anywhere in the supply chain can lead to food quality or food safety risks for consumers, and negative outcomes reflect poorly not just on the businesses involved but on the industry as a whole.

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 [9, 40].

V. parahaemolyticus modeling. Temperature data loggers combined with risk models provide a powerful tool for assessing cold chains. We found that three in four oysters shipments had a net decrease in *V. parahaemolyticus* from harvest to food retail/restaurant. We attribute the findings of *V. parahaemolyticus* growth to either slow cooling during post-harvest processing or breakdowns in the cold chain. Harvesting and processing oysters in accordance with state VCP regulations did not always prevent *V. parahaemolyticus* growth according to the model. Conversely, when oyster temperatures were above VCP regulations at harvest, the models occasionally found no net growth of *V. parahaemolyticus* if other stages of the supply chain remained in compliance with VCP regulations. These 'exceptions to the rule' suggest that the positive and negative predictive value of VCP regulations, relative to the outcome of *V. parahaemolyticus* growth, should be further explored.

The growth model we used was validated for *C. virginica* oysters [41], but has not been validated for *C. gigas* oysters. The significance of our Washington State *Vibrio* model findings should be interpreted with caution until the model is validated. Others have developed *V. parahaemolyticus* models for oyster slurry [42], which may not be relevant for whole live oystesr, and *C. gigas* oysters [43]. Future work could compare these models to the U.S. Food and Drug Administration model under real world conditions and attempt to validate the models using *V. parahaemolyticus* cultures at various stages of the supply chain.

Recommendations. Based on our findings, we offer a list of recommendations for the oyster industry; broken out into advice for oyster producers, businesses that handle shellfish, and policy.

Recommendations for oyster producers:

- Review state Vibrio Control Plans [44] and strive to meet or exceed regulatory time and temperature requirements;
- Remember that the most critical windows in which to control the growth of Vibrio bacteria in the supply chain are immediately after harvesting and during post harvest processing;
- Use ice slurries or layered ice for cooling, which have been found to be more effective to control the growth of Vibrio bacteria than mechanical refrigeration alone [45-47].

Recommendations for businesses than handle shellfish:

- Verify that Hazard Analysis and Critical Control Point (HACCP) plans are being followed and are working appropriately to reduce Vibrio bacterial growth caused by time and temperature abuse. Regularly review procedures for monitoring, corrective action, verification, and recordkeeping systems [48];
- Use oyster temperature sensors i) within your facility and ii) in shipments one-up and one-down in your supply chain to verify that procedures and practices are working properly and are in compliance with food safety guidelines;
- Perform practice recalls to verify that there is one-up and one-down traceability in your supply chain.

Policy recommendations for government and industry:

- Develop guidance for the shellfish industry regarding best practices for domestic and international air freight shipments;
- Develop tools to assist shippers in making packaging decisions. One option is an online calculator where shippers could manipulate input variables (e.g., package type, insulation R-value, starting temperature of oysters, starting temperature of frozen gel packs, estimated time of travel, ambient air temperature, etc.) to determine what combinations of variables would meet oyster temperature criteria during shipping;
- Establish a working group within the Interstate Shellfish Sanitation Conference to address issues related to cold chains and microbial growth;
- Validate the Food and Drug Administration Vibrio risk calculator for Pacific oysters (*C. gigas*).

Study Limitations.

There were several limitations to our study, and they are mentioned here to explain the scope of work and limits to data collection and/or ability to generalize the study findings.

- 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 proposed to study three types of supply chains: i) direct-market; ii intermediated supply chains; and iii) mainstream supply chains in two study regions. When we began identifying the actual supply chains used by the oyster industry, we found that intermediated and mainstream supply chains look very similar and so we merged these two variables together in the analysis.

- We were not able to share maps of the geographic relationship among participants because of concerns over confidentiality. We initially did these types of maps in year 1, and shared them with participants, but were asked not to report them publicly.

- 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.

- Our sampling was skewed toward warm seasons when temperature control is more challenging, therefore we expect that a random sample throughout the year would find lower rates of temperature abuse.

- We did not assess whether temperature affected oyster quality. This would have required a tasting panel to assess deterioration in food quality (i.e., changes in flavor, texture, color, or liquor loss). Due to cost and other factors, we did not include this research question in our study proposal.

- We did not assess whether temperature affected oyster survival. To answer this question, retailers would have had to count the number of mortalities in each box. We thought this was overly burdensome to ask participating retailers. Therefore, we did not include this research question in our study proposal

- We did not measure the actual amount of *V. parahaemolyticus* in oysters. However, we recruited a colleague to model *V. parahaemolyticus* in oysters using our temperature data. This was not a part of the original proposal, but ended up being hugely helpful in determining the human health risks associated with temperature abuse.

- We tracked just two shipments to Hong Kong, which limits our ability to make generalizations about international supply chains. Future work should focus on more international shipments.

Future Work.

We identified a series of ideas that could be included in future NOAA funding opportunities or by other researcher:

- We heard from several people who were interested in repeated the temperature sensor methods in other oysters growing regions such as the Gulf of Mexico or the Northeast.

- We would like the FDA to validate the *V. parahaemolyticus* model for *C. gigas* oysters

- Additional work could explore how the other measures of performance of supply chains (other than temperature) affect shellfish quality, safety, and price.

- Research could continue exploring aquaculture's role in local, regional, national, and international food systems.

Evaluation

We achieved the project goals and objectives, by collecting and analyzing data in support of each component over the study period. We are in the process of implementing a communication plan to share the findings with many different groups of stakeholders in the industry, academia, and government. Two modifications were made to the objectives. One being the merging of intermediated and mainstream supply chains, because in practice, these types of chains function very similarly. The solution we chose was to combine intermediated and mainstream supply chains together in the analysis. A second modification was the decision not to report maps of supply chains because participants were concerned could be used to identify them-- making the study participants no longer confidential. The solution we chose was to produce maps that were at a scale that would not compromise study participants, for example, by mapping supply chains at the state level and not showing intermediate stops at wholesalers, and by generating cartoons that represent supply chains.

Dissemination of project results:

Below is a list of the conferences, peer reviewed manuscripts, and science communication activities we have performed. We anticipate issuing a press release after the publication of the final manuscript in Fall 2019. We will attempt to get these findings picked up by print and web news outlets. To better inform the industry of our findings, we have published an Extension Factsheet through Virginia Cooperative Extension, submitted a magazine article to the World Aquaculture Society, and will be submitting two newsletters for the East Coast and Pacific Coast Shellfish Growers Associations' fall newsletter. We have also collected email address from all participants and will email them with study findings.

Conference presentations:

- Pacific Coast Shellfish Growers Association, Oregon, Sept 2019
- Aquaculture America, New Orleans, March 2019
- Atlantic Gulf Coast Seafood Technology conference, Boston March 2019
- Pacific Coast Shellfish Growers Association, Washington, Sept 2018
- National Shellfisheries Conf, Washington, March 2018
- Washington Sea Grant, Washington, March 2018
- National *Vibrio parahaemolyticus* Workshop, Baltimore, Sept 2017 (attended, no presentation)

Peer reviewed publications:

Love, D. C., Lane, R. M., Davis, B. J., Clancy, K., Fry, J. P., Harding, J. and Hudson, B. 2018. Performance of Cold Chains for Chesapeake Bay Farmed Oysters and Modeled Growth of Vibrio parahaemolyticus. Journal of Food Protection 82**:** 168-178. https://jfoodprotection.org/doi/full/10.4315/0362-028X.JFP-18-044

Love, D. C., Kuehl, L. M., Lane, R. M., Fry, J. P., Harding, J., Davis, B. J. K., Clancy, K. and Hudson, B. 2019a. Performance of Cold Chains and Modeled Growth of *Vibrio*

parahaemolyticus for Farmed Oysters Distributed in the United States and Internationally. International Journal of Food Microbiology (*accepted Oct 2019*).

Love, D. C., Lane, R. M., Kuehl, L. M., Hudson, B., Harding, J., Clancy, K. and Fry, J. P. 2019b. Performance and Conduct of Supply Chains for United States Farmed Oysters. Aquaculture (*accepted Oct 2019*).

Non-peer reviewed articles:

Lane, B., Love, D.C., Kuehl, L., Hudson, B. 2019. Application of Time-Temperature Indicators and Time Temperature Data Loggers in the Seafood Industry. Virginia Cooperative Extension publication FST345NP. Available at www.pubs.ext.vt.edu/FST/FST-345/FST-345.html

Hudson, B., Love, D.C., Lane, B. Fall 2019 (*planned*). Shipping Shellfish Safely: Lessons from US Oyster Supply Chains. Longlines newsletter. Pacific Coast Shellfish Growers Association.

Hudson, B., Love, D.C., Lane, B. Fall 2019 (*planned*) Shipping Shellfish Safely: Lessons from US Oyster Supply Chains. ECSGA newsletter. East Coast Shellfish Growers Association.

Love, D.C., Lane, B., Hudson, B. Oct 2019 (*in review*). Shipping Live Seafood Safely: Lessons from US Oyster Supply Chains. World Aquaculture Society Magazine. World Aquaculture Society.

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Tables and Figures

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, 1 - 10% to direct market
Chesapeake Bay	6	53 (10-163)	100 (99-100)	
Wholesaler				
Broadline	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

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
	Shuckability
Marketing and sales:	Shell quality
Attractive packaging	Taste and texture
Branding and storytelling	Unique brand name
Large volumes for sale	
Reliability	**Marketing and sales:**
Reputation	Customer experience
Same day shipments	Knowledgeable staff
Unique brand name	Locally sourced oysters
Year-round sales	Menu rotates frequently
	Price
Other:	Sourced from a reputable seller
Economic sustainability	Variety of oysters available (geography and salinity)
Environmental sustainability	
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	1,914	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	5,097	5.4 ± 2.1	33	33
National (ground)	15	5.0 ± 1.8	1,389	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)

Table 4. Product recall and traceability in oyster supply chains.

Supply chain stage	Product recall (%)	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

Table 5. Number of companies participating in the study and number of shipments of oysters with temperature sensors.

Supply Chain	Washington State	Chesapeake Bay [a] (Love et al. 2019)	Total
Shipments			
Domestic	60	63	123
International	2 [b]	0	2
Total	62	63	125
Company type			
Producer	7	6	14
Wholesale	35 [c]	3	38
Restaurant	29	28	57
Food retail	4	4	8
Consumer	1	2	3
Freight carrier [d]	21	6	27
Total	97	49	147

[a] includes several participants outside the Chesapeake Bay region that were not included in [49]
[b] two shipments to Hong Kong, China
[c] One wholesaler was a participant in both Washington State and Chesapeake Bay supply chain studies.
[d] Washington State: 7 air freight, 7 ground freight, 4 freight forwarders, 2 direct-to-consumer freight; Chesapeake Bay: 1 air freight, 4 ground freight, 1 direct-to-consumer freight

Table 6. Study population in the Chesapeake Bay and self-reported cold chain temperatures.

Supply chain	Sample size		Median cold chain temperature (°F) (range)			Ice use (%) [b]
	Temp study	Interviews	Receiving room	Live room/ Refrigerator	Truck	
Producer	6	6	-	42 (38-50) [a]	-	50
Freight carrier	5	4	-	-	34 (33-36)	25
Wholesale	2	2	34.5 (34-35)	40 (38-42)	37 (36-38)	50 [c]
Food retail/ Restaurant	26	13	-	38 (29-40)	-	58
Total	39	25	-	-	-	52

[a] measured by researchers
[b] the denominator is the interview sample size
[c] ice used only in delivery

Table 7. Temperature control during oyster harvesting and on-farm processing during six farm visits, June to September, 2017.

Producer code	Harvest temp (°F)		Ice (yes/no)	Refrigerator temp (°F)	Time (hr) to achieve:		Oyster internal temp at pick-up (°F)	Ideal product temp (°F) [d]
	water	air			Environment temp <45 °F	Oyster internal temp <50 °F		
P1	80	70	yes [a]	44	4.0	4.5	47.3	40-45
P2	70	72	no	50	2.5	10.2	50.6	37-40
P3	71	70	yes [b,c]	38	1.8	8.9	41.5	41
P4	70	70	no	40	3.0	3.1	46.9	<50
P5	76	72	yes [a,b]	38	2.4	4.4	39.0	<45
P6	72	68	no	45	1.2	3.3	42.8	40

[a] layered ice
[b] ice slurry
[c] P3 typically uses an ice slurry to remove worms, but did not use an ice slurry on the day we visited.
[d] based on interviews with producers

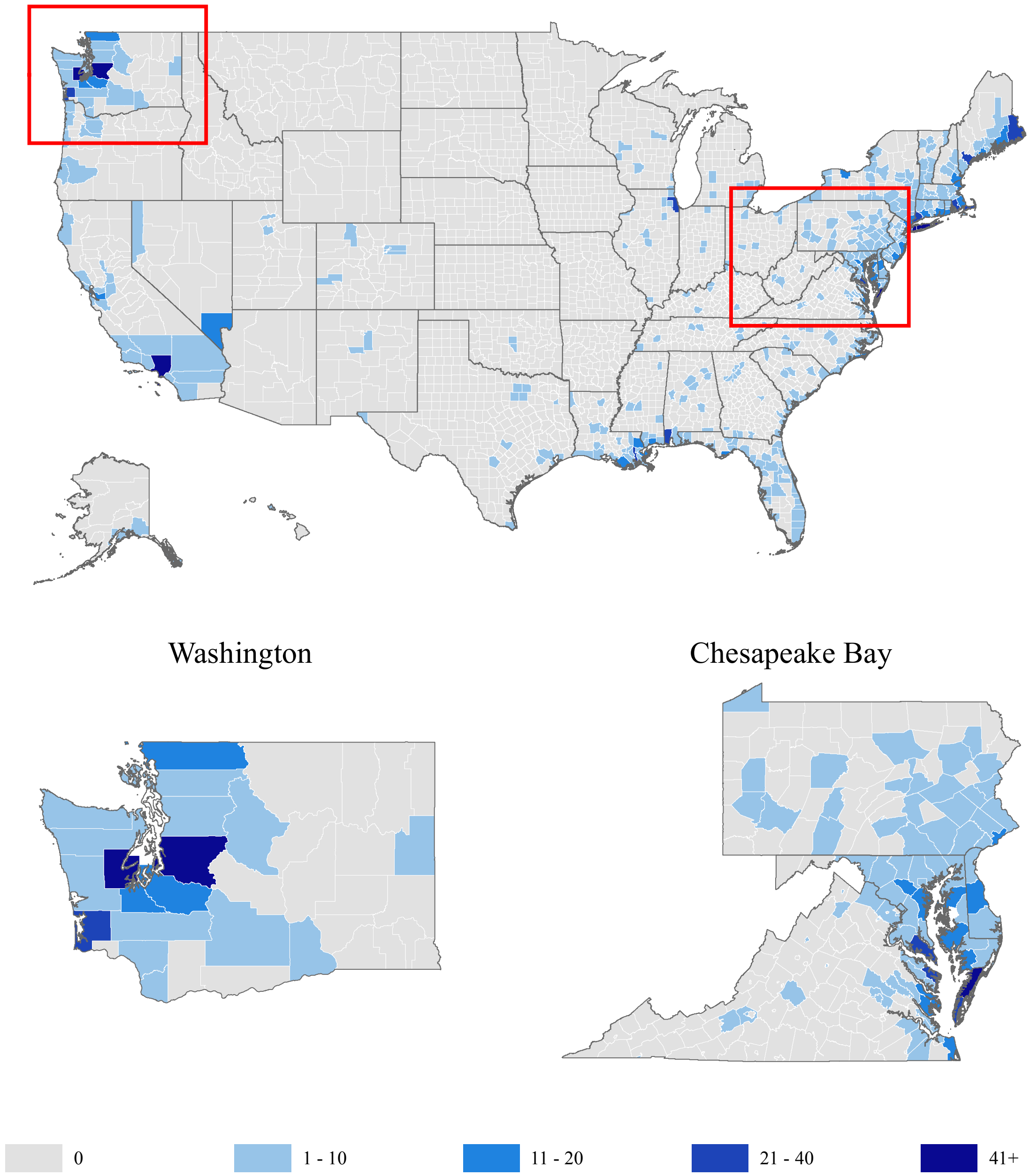

Figure 1. Certified shellfish producers, processors, and distributors by county. Data collected September, 2017 [50].

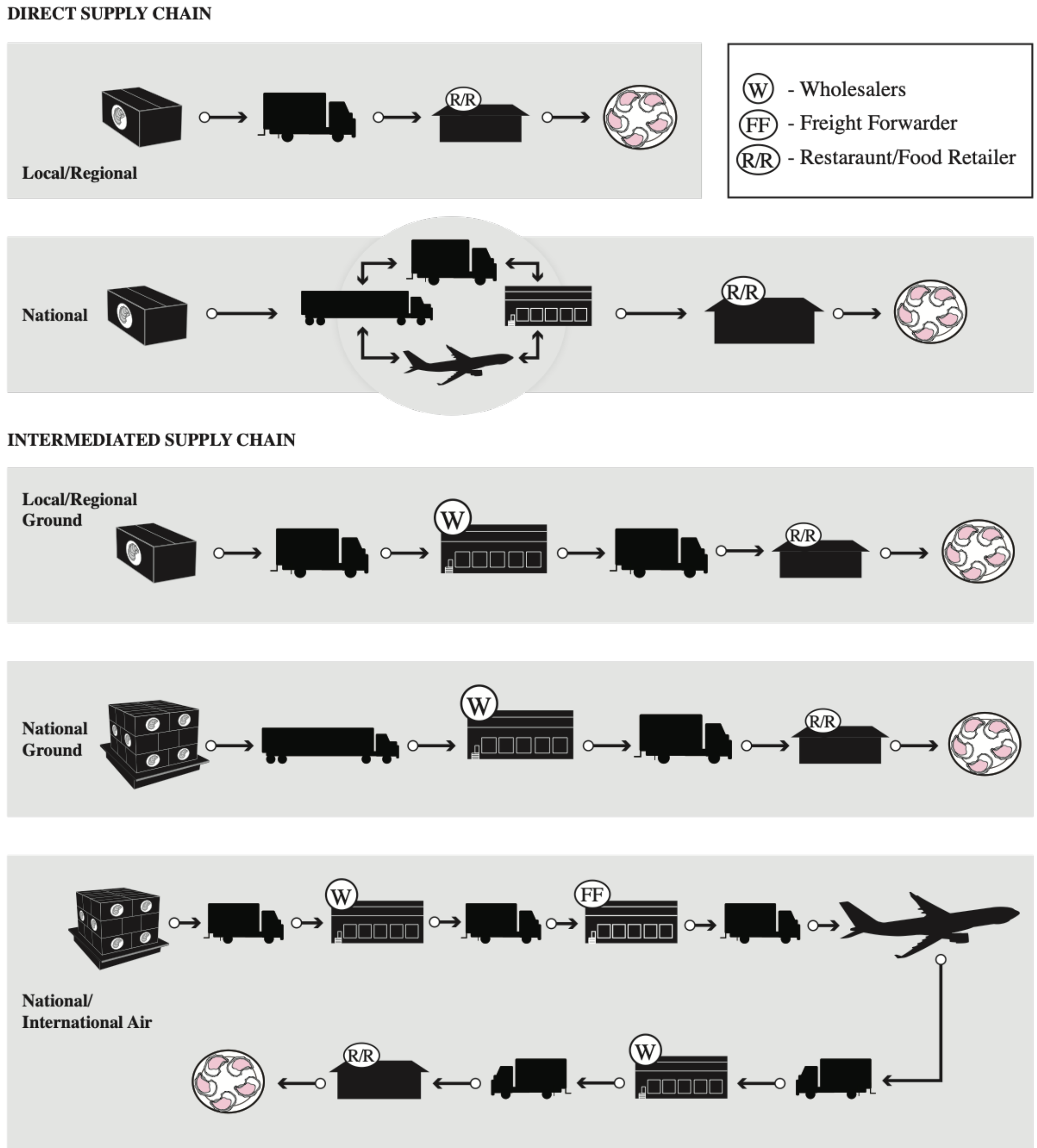

Figure 2. Direct and intermediated supply chains for U.S. farmed oysters. The figure was created by tracking the supply chains for 125 oyster shipments made by participants. W = wholesale; FF = freight forwarder; R/R = restaurant and/or food retailer

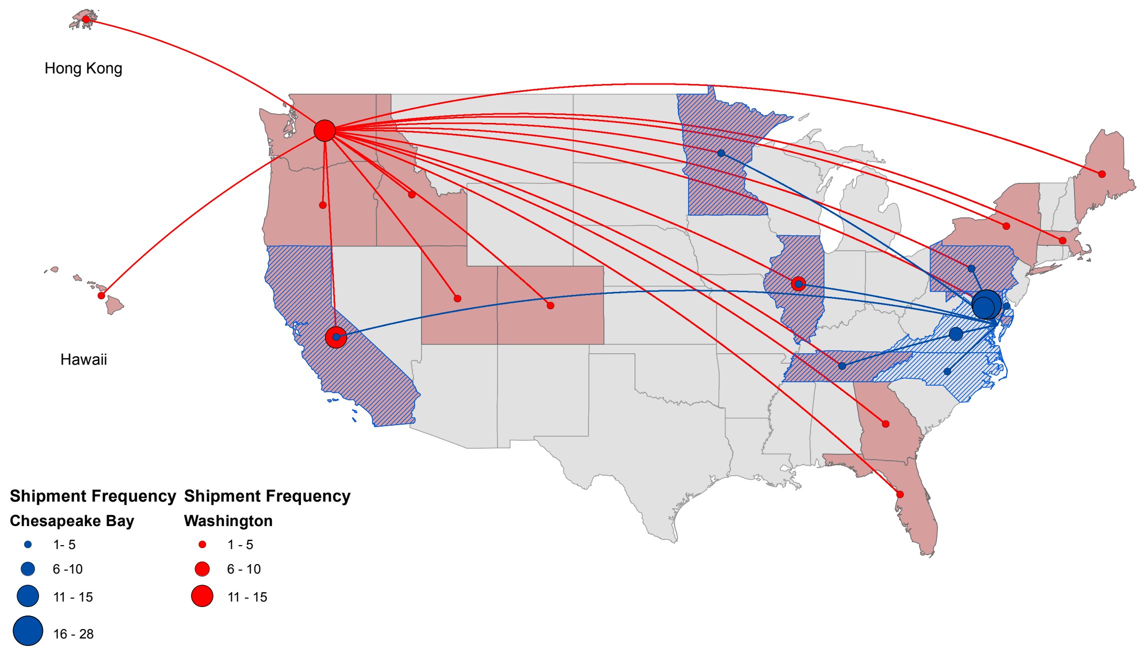

Figure 3. Destinations for Chesapeake Bay oysters shipped in 2017 (blue, n = 63) and Washington State oysters shipped in 2018 (red, n = 62). Shipments were made to 20 states, Washington D.C., and Hong Kong, China. This figure includes all shipments made in the study, regardless of whether the temperature sensors were returned. In the Chesapeake Bay portion of the study, sensors from 51 of 63 shipments were returned, and in Washington State, sensors from 52 of 62 shipments were returned.

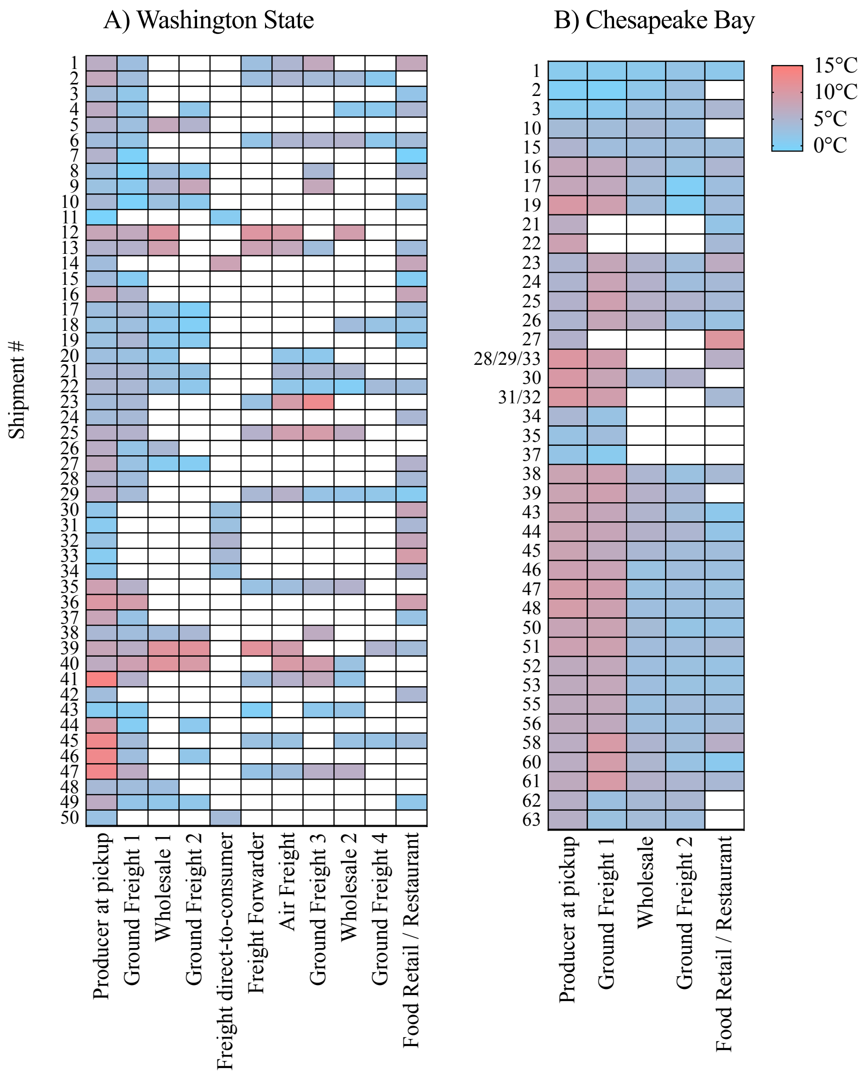

Figure 4. Temperature gradient plots for all oyster shipments (rows) by stage of supply chain (columns) for A) Washington State oysters and B) Chesapeake Bay oysters. Each cell represents the average internal temperature of oysters. Supply chain stages that were not used are presented as empty cells.

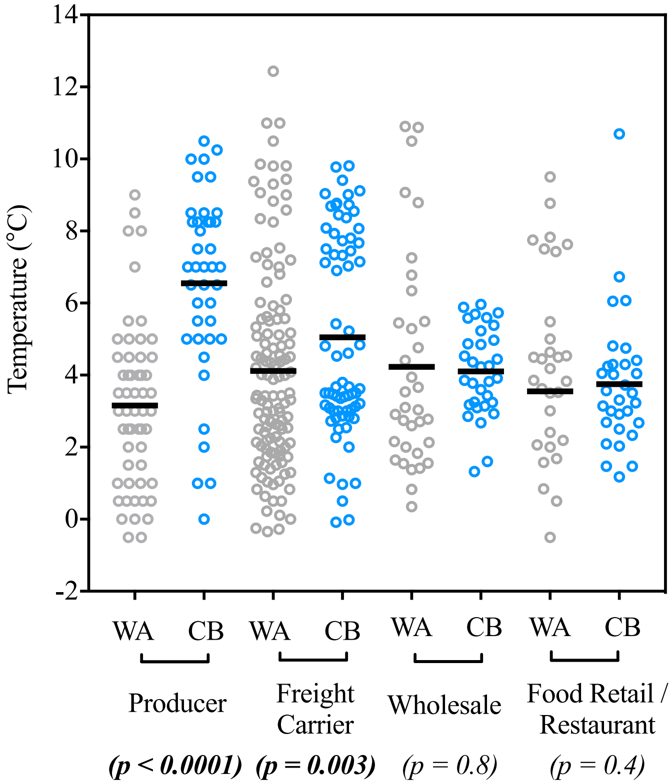

Figure 5. Strip plot and mean (black bars) of internal oyster temperatures for Washington State (WA, grey) and Chesapeake Bay (CB, blue) farmed oyster supply chains. Sample sizes are reported in Table A.1. P values in bold are statistically significant. Y-axes are in °F and °C.

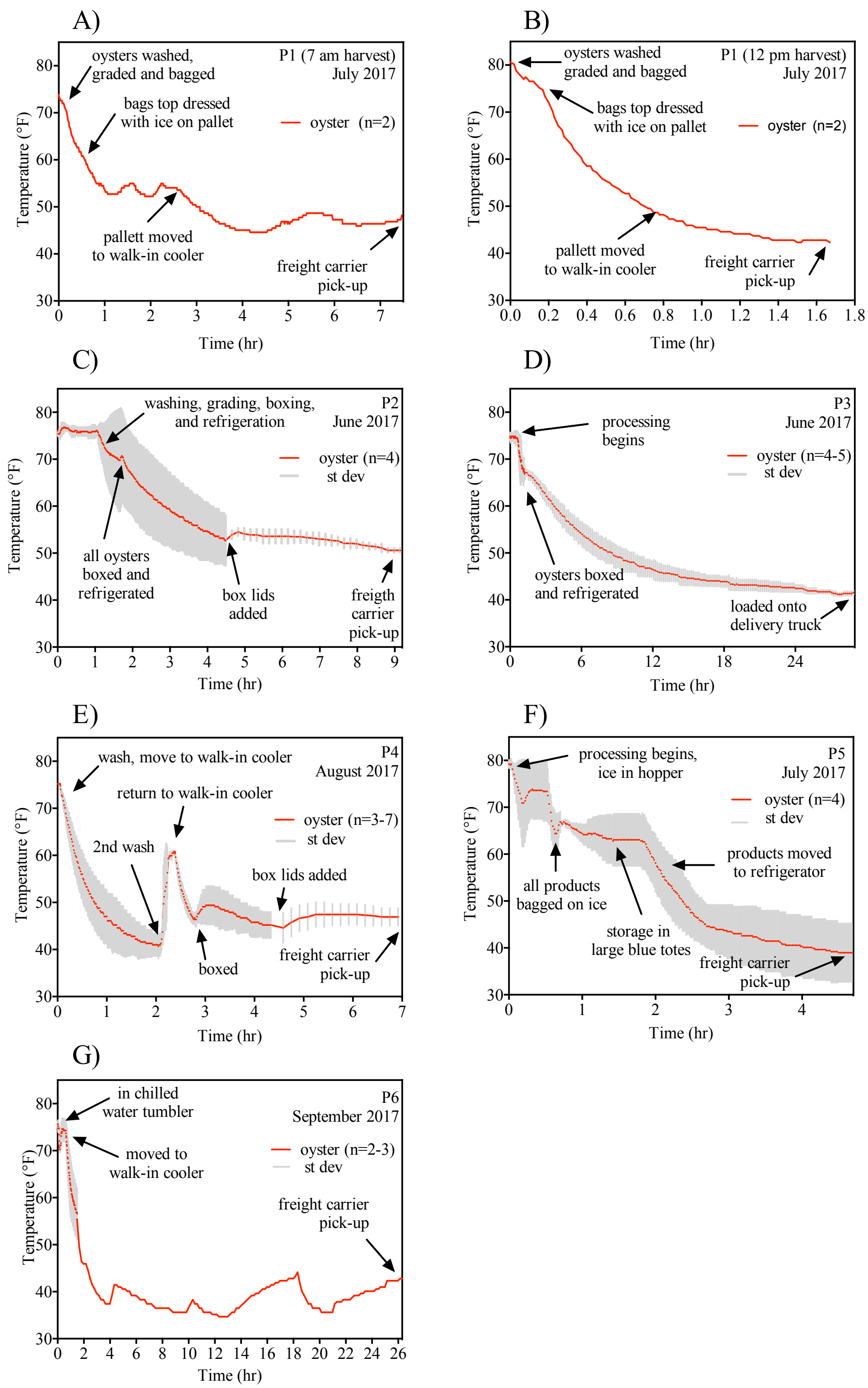

Figure 6. Internal oyster temperature during harvest and on-farm processing at six farms in the Chesapeake Bay. A) and B) are from Producer 1 (P1) at two time points on the same day, C) is Producer 2 (P2), D) is Producer 3 (P3), E) is Producer 4 (P4), F) is Producer 5 (P5), and G) is Producer 6 (P6). Note the x-axis varies by figure. Grey bars indicate standard deviation, the red line is the mean. The sensor sampling interval was 1 min for the first few hours and then switched to 10 min intervals to preserve sensor memory for supply chain readings.

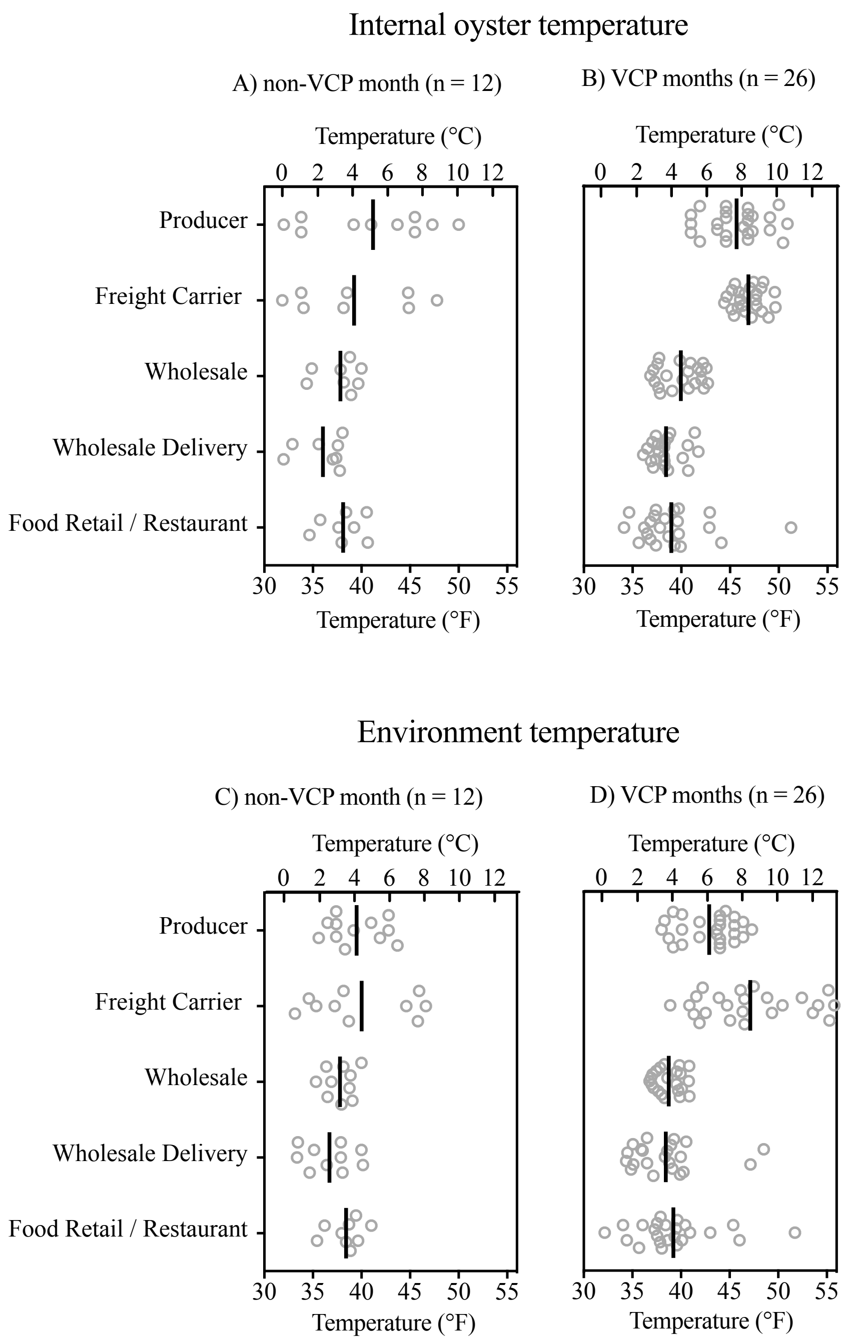

Figure 7. Strip plots of A) internal oyster temperature and B) environment temperature for shipments in *Vibrio* Control Plan (VCP) months (n=26) and a non-VCP month (n=12). Scatter plots are presented by step of the supply chain; the black bar is the mean value and grey circles are individual samples. Producer values are point estimates for the temperature before pick-up by freight carrier trucks, while all other steps of the supply chain are reported as the average temperature reading for each sample.

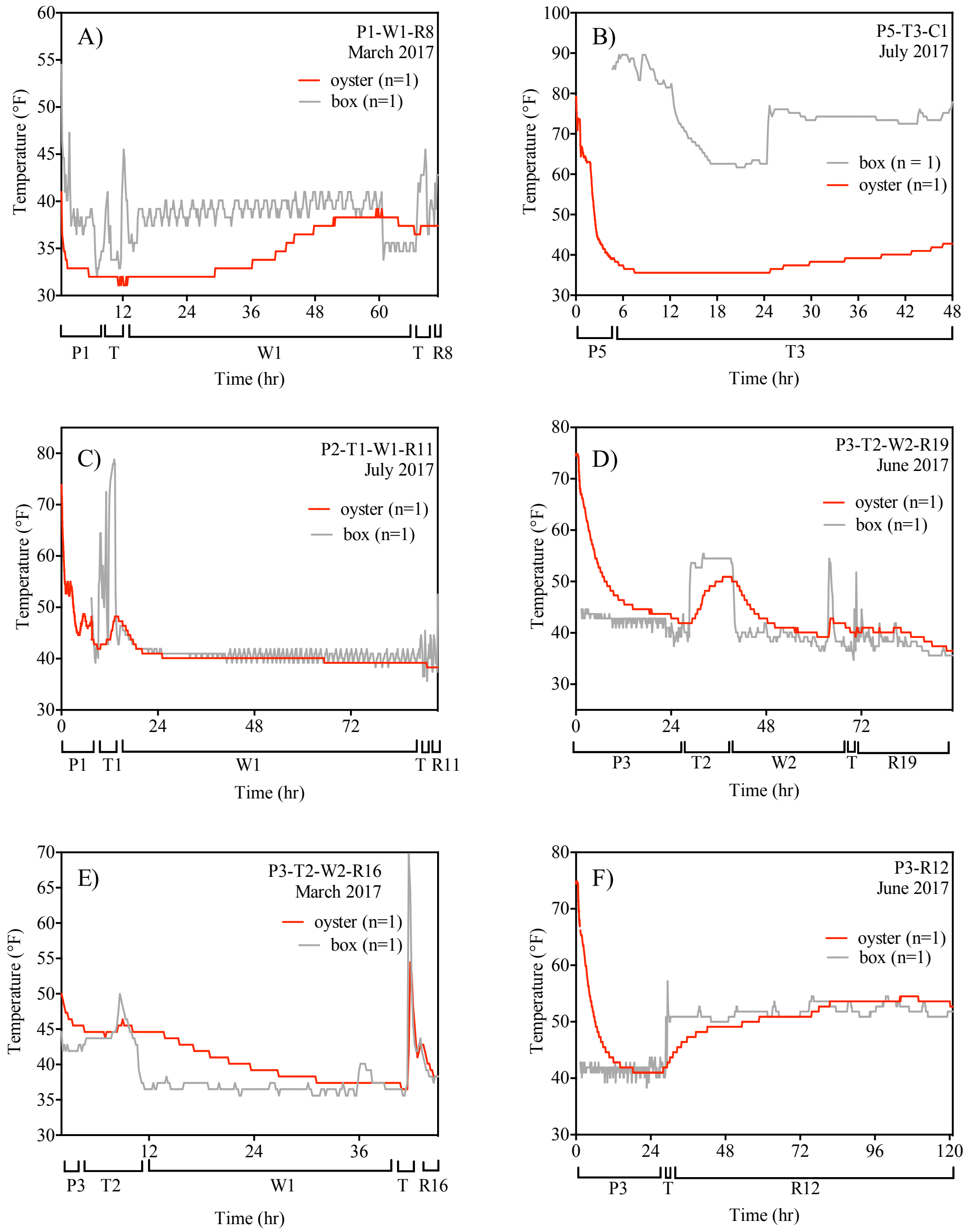

Figure 8. Six examples of temperature-related issues in Chesapeake Bay farmed oyster cold chains. Temperature profiles for all oyster shipments are provided in the Supporting Information section. Temperature profiles of internal oyster temperatures and environment temperatures from harvest to food retailers/restaurants. The sensor sampling interval was 1 min at the oyster producer and 10 min in the supply chain. P = producer; T = freight carrier (truck); W = wholesale; R = food retailer or restaurant; C = consumer. The number following P, T, W, or R was assigned to each participant to provide anonymity.

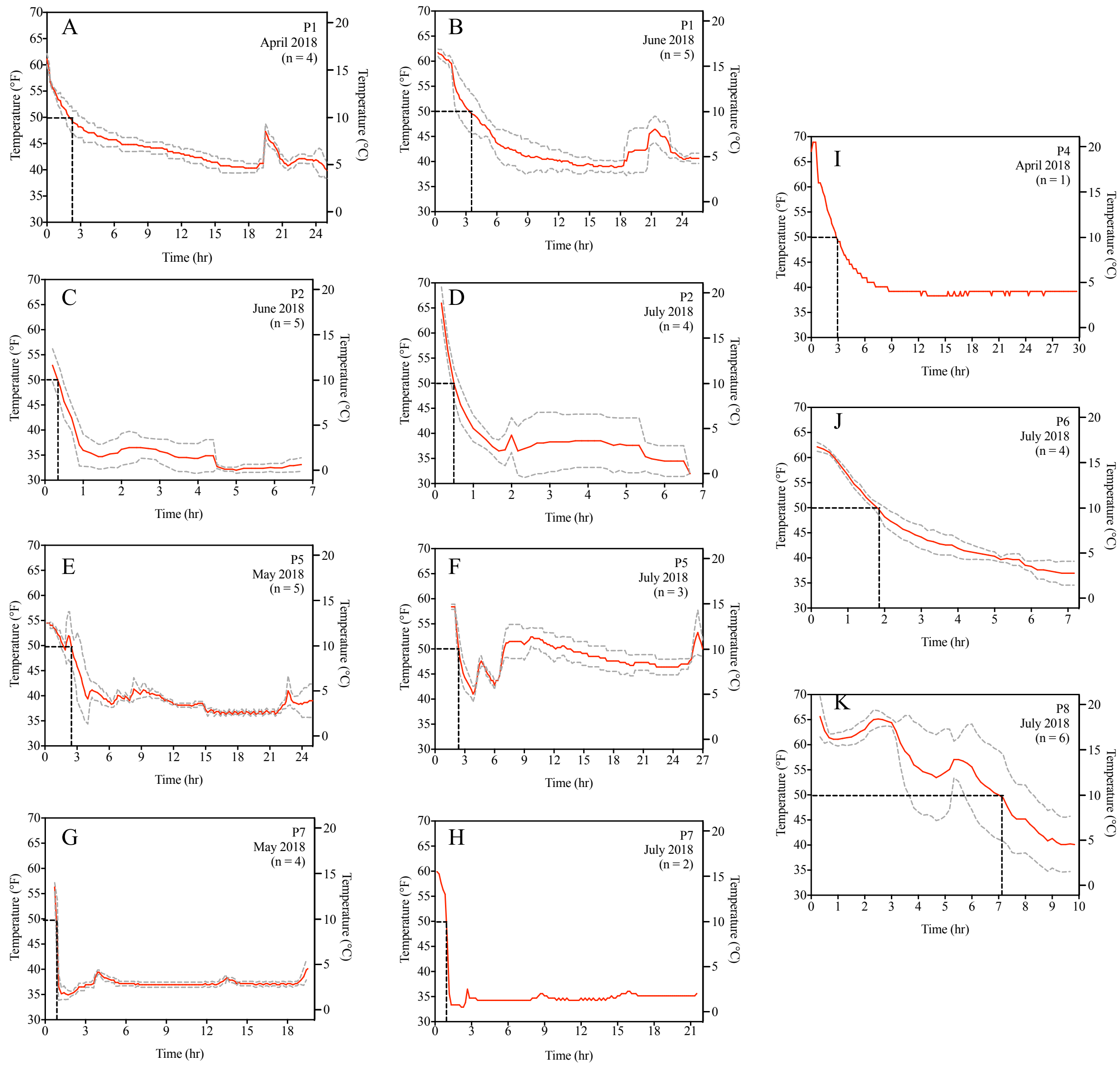

Figure 9. Internal oyster temperature during harvest and on-farm processing at eight farms in Washington State. Graphs represent time from harvest to when the box or bag of oysters left the farm property. Y-axes are in °F and °C. Several farms had repeat visits (A and B; C and D; E and F; G and H). Grey lines indicate standard deviation, red lines indicate the mean. The sensors took readings at 10 min intervals.

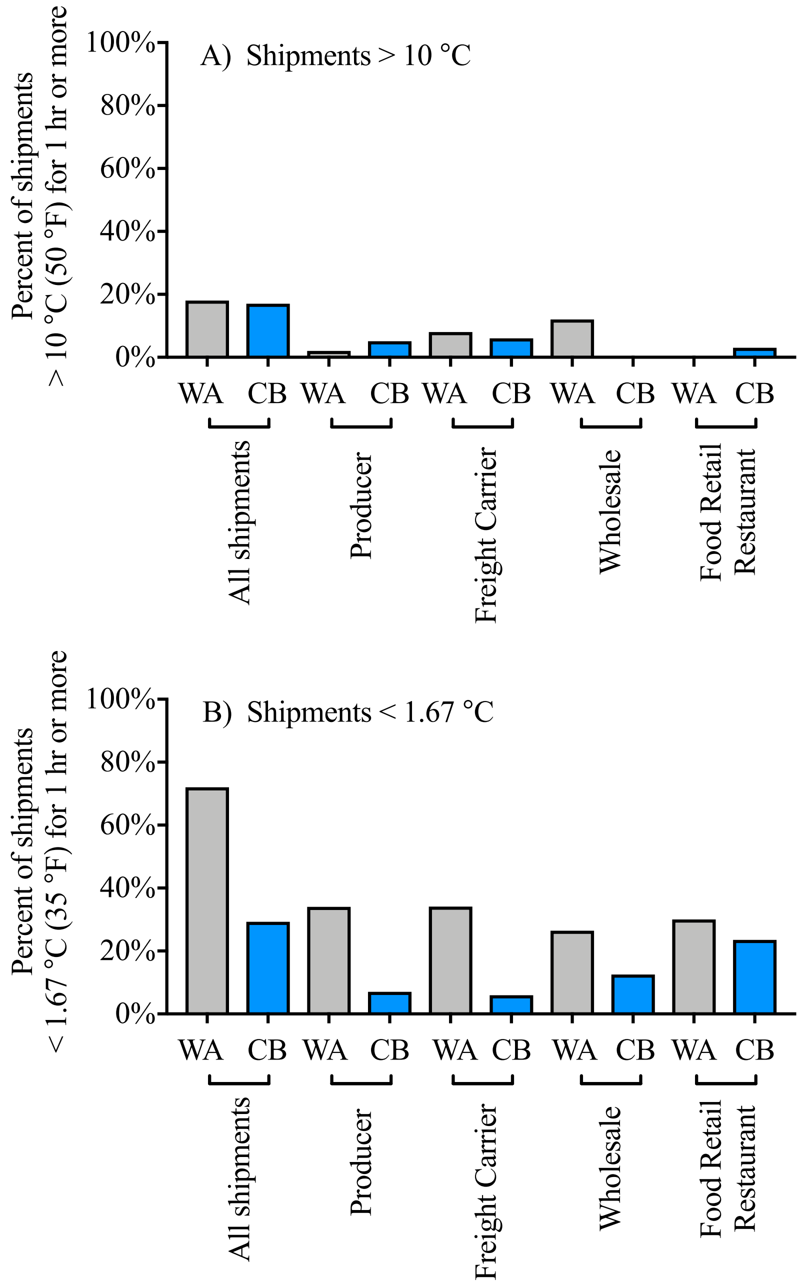

Figure 10. Frequency of shipments and supply chain participants with internal oyster temperatures A) > 10 °C (50 °F) and B) < 1.67 °C (35 °F) for Washington State (WA, grey) and Chesapeake Bay (CB, blue) farmed oyster supply chains. Sample sizes are reported in Tables A.2 and A.3.

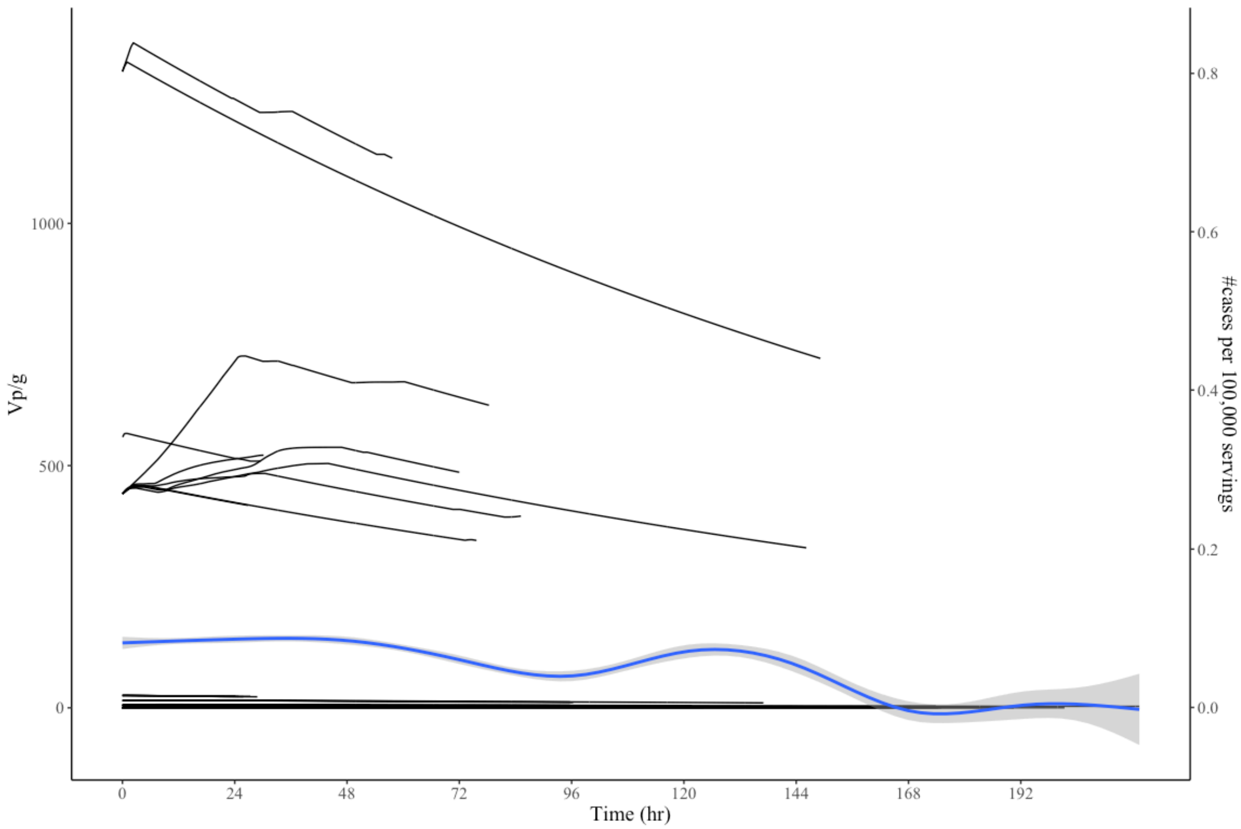

Figure 11. Estimated *Vibrio parahaemolyticus* abundance per gram oyster tissue (left y-axis) and the risk of illness as cases per 100,000 servings (right y-axis) from oysters produced in Washington State and shipped locally, nationally, and internationally. X-axis represents time elapsed since harvest. Estimations of the left and right y-axes can be displayed simultaneously due to the linear approximation of the Beta-Poisson dose-response model. Vibrio abundance at harvest was estimated based on Washington State Department of Health *V. parahaemolyticus* monitoring, and growth in supply chains was calculated using iterative temperature-based models. The black lines represent the abundance or risk of individual oyster shipments. The blue line depicts the mean abundance or risk across all oysters estimated by using a generalized additive model and the grey band displays the corresponding 95% confidence interval.

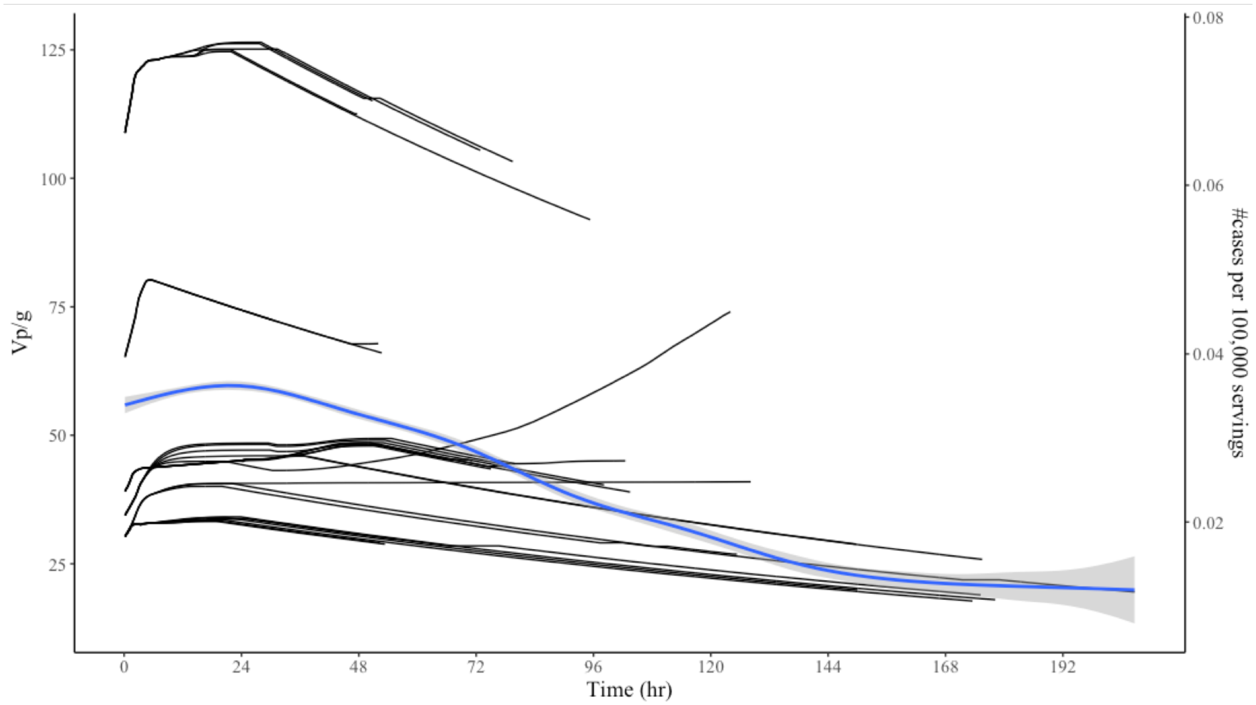

Figure 12. Estimated *Vibrio parahaemolyticus* abundance per gram oyster tissue (left y-axis) and the risk of illness as cases per 100,000 servings (right y-axis) from oysters produced in the Chesapeake Bay and shipped to surrounding states. Estimations of both can be displayed simultaneously due to the linear approximation of the Beta-Poisson dose-response model. *Vibrio* abundance at harvest was estimated based on water temperature, and growth in supply chains was calculated using iterative temperature-based models. The blue line provides the mean abundance/risk across all oysters estimated using a generalized additive model and the grey bar displays the corresponding 95% confidence interval.

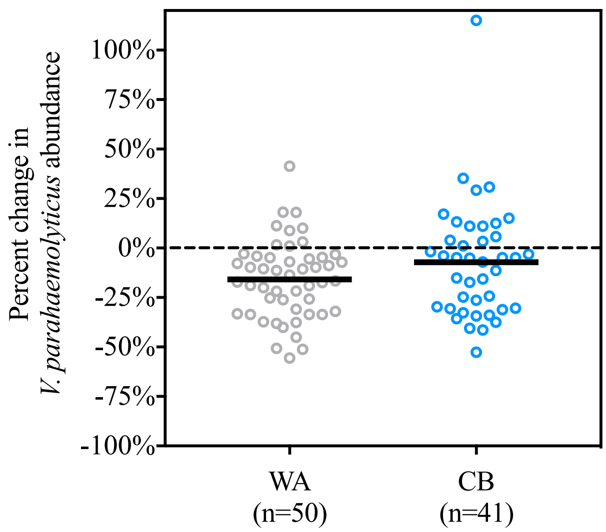

Figure 13. Strip plot of modeled percent change in *Vibrio parahaemolyticus* abundance in Washington State oyster shipments (grey circles) and Chesapeake Bay oyster shipments (blue circles). The percent change was calculated as the final *V. parahaemolyticus* abundance (at food retail/restaurant) minus the initial *V. parahaemolyticus* abundance (at harvest) divided by the initial *V. parahaemolyticus* abundance. The dashed line represents no change in *V. parahaemolyticus* abundance.

Appendix

Oyster Supply Chain Survey Tool
Washington, 2018

Part A. Background Information

What is your title? What are your main work responsibilities? How long have you been in this position?

How many employees work at your business?

Part B. Cold Chains

Can you walk us through a typical harvest day? (*Producer*)
  Probe: How many days per week do you harvest oysters? How are oysters processed? How do you decide if an oyster is harvestable?
Can you walk us through a typical oyster delivery to your facility? (*Freight Carrier, Wholesale, Food Retail, Restaurant*)
  Probe: What do you look for when products arrive?
What steps are taken to cool oysters and to keep them cool once they're at temperature?
  Probe: Do you use ice? Do you use a walk-in refrigerator? What temperature is your refrigerator set to? What is your ideal temperature for oysters in your facility (and in delivery)? Is there anywhere in your facility (or boat) where temperature is difficult to maintain?
Is cold abuse or gaping an issue for your products? How do you protect against cold abuse?
How do practices differ during summer months (e.g. when *Vibrio* control plans are in effect)?
(*Producer*) How many employees have taken the Department of Health *Vibrio* training?

Part C. Supply chains

What brands of oysters do you sell?
  Probe: What species? What size classes? From what growing regions?
Who do you purchase oysters from? (*Wholesale, Retail*)
  Probe: Do you purchase market-sized oysters from other producers? (*Producer*), What percent of products comes from WA? What percent comes from elsewhere on the west coast? (*Wholesale, Food Retail, Restaurant*)
Who buys your product?
  Probe: Where are your customers located? What percent of sales are associated with each buyer? Do you export to other countries? (*Producer, Wholesale*)
  Do you sell direct to consumers? (*Producer*) [possible answers: farmers markets; roadside stand; from your home or business; direct sales to restaurants, institutions, food hubs; internet sales; community supported fishery; other]
On average, how many market-sized oysters do you sell per week? (or ship per week for *Freight Carrier*)
  Probe: Are there seasonal trends or peak times?

How are oysters delivered to customers?

Probe: Do you own or lease your own refrigerated trucks? If not, who are your freight carriers? Are there any additional steps taken to ensure temperature control is maintained during shipment?

Does your business sell other products besides oysters? If so, what percent of sales come from market-sized oysters? (*Producer, Wholesale*)

Part D. Traceability

What data elements does your business record about oysters you produce, transport, buy, or sell?

Probe: Does your business keep track of lot numbers? What events or activities trigger collection of these data (such as when product is harvested, a box is filled, products are aggregated or disaggregated, etc)? What format are the records kept? How long are these records maintained?

What information do you share with buyers or sellers on an ongoing basis about products you purchase or sell?

What information do you share to establish new business relationship (such as HACCP plans, permits, or a credit check)?

In the event of a product recall, does your business have the ability to track shipments made to businesses you directly buy from or sell to?

Probe: Do you engage in practice recalls?

Has your business been involved in any product recalls?

Probe: Can you explain what happened? What businesses and state agencies were involved? How much product was discarded? Were you satisfied with how the recall was handled? How could the recall have been improved? Would better traceability limit the scope and size of the recall?

What areas could your business improve upon to enhance traceability?

Probe: If the current paper tag included a digital component (bar code or QR code) that could link to digital information do you think that would help your business?

Part E. Challenges and Opportunities

What are the biggest challenges for you in operating your business?

Is there anything you would change about regulations or how they are implemented for oyster production and distribution in Washington?

Oyster Supply Chain Survey Tool
Chesapeake Bay, 2017

Part A. Background Information

What is your role/position at the business? *(all participants)*

How long have you worked at the business? *(all participants)*

How many employees work at the business? Full-time? Part-time? *(all participants)*

What types of oysters do you raise? (species, diploid or triploid, spat-on-shell or single oysters?) What brands do you carry? What methods do you use? (floats, bags, racks, bottom culture) *(Producer)*

How many stores do you have and where are they located? How many covers a night do you do? How many stations are in the kitchen? (*Retail/Restaurant)*

Does your business buy/distribute/sell any other product besides oysters? What percent of food sales come from oysters? Farmed vs wild oysters? *(Producer, Wholesale, Retail/Restaurant)*

Part B. Supply Chains

Could we draw a map of what your supply chain looks like? (*Producer, Wholesale, Food Retail, Restaurant*)

Who do you sell to and/or purchase oysters from? Who do you use for shipping? (*Producer, Wholesale, Food Retail, Restaurant*)

Do you sell direct to consumers? If yes, where do you sell your product? (*Producer)*
(Farmers market; Roadside stand; From your home; Direct sales to restaurants, institutions, food hubs; Internet sales; Community supported fishery; Other)

Do you have a year-round demand for farmed oysters? (*Producer)*

How many days per week do you harvest oysters? (*Producer)*

Can you tell me about your fleet of trucks? How many? What size are the trucks? (*Freight Carrier)*

Geography of sales: Where are your largest customers located? Do you export to other countries? (*Wholesale)* What brands do you carry from the region and outside the region? (*Food Retail, Restaurant)* What geographic range do you cover? (*Freight Carrier)*

Product ordering, stocking, and distribution: How do you decide what brands of oysters to carry? How much inventory do you keep on hand? How do you decide the base quantity to have on hand? (*Wholesale, Food Retail, Restaurant)*

On average, how many oysters do you sell per week? (*Producer, Wholesale, Food Retail, Restaurant*)

What factors are important to the customer when buying oysters? (*Food Retail, Restaurant)*

How do you educate the front of the house? (*Food Retail, Restaurant)*

How do you distinguish yourself from your competitors? (*Producer, Wholesale, Food Retail, Restaurant*)

<u>Part C. Communication with Customers</u>

How do you develop new relationships with buyers/sellers? What qualities are important to you in a new business relationship? What are red flags for you? (*Producer, Wholesale, Food Retail, Restaurant*)

What requirements, standards, and paperwork do new buyers request of you (do you request from new sellers)? (minimum order quantity and frequency, product specifications, labeling, insurance, HACCP, etc.) (*Producer, Freight Carrier, Wholesale, Food Retail, Restaurant*)

How often do you communicate with retailers? (e.g., sales and marketing etc.) (*Wholesale*)

Do you provide/receive feedback, education, or technical assistance from buyers/sellers to improve product/processing quality? Are there ever any issues with buyers/sellers, what transpired, and how was it handled? (*Producer, Wholesale, Food Retail, Restaurant*)

<u>Part D. Cold Chain</u>

Could we walk through your facility*?* (for in person interviews) (*Producer, Freight Carrier, Wholesale, Food Retail, Restaurant*)

Where are oysters stored at your facility? (*Producer, Freight Carrier, Wholesale, Food Retail, Restaurant*) How are oysters stored on your boat during harvest? (*Producer)*

How are oysters packaged shipped to/from your facility? (*Producer, Wholesale*)

Does your business do any processing, repackaging, comingling, or wet storage? Do you add new tags or labels to products? (*Wholesale*)

What are optimal temperatures for oysters on your boat during harvest? (*Producer*) What are optimal temperatures for oysters in your facility and in shipments? *(Freight Carrier, Wholesale, Food Retail, Restaurant*)

How is temperature monitored during harvest? Is water temperature monitored? (*Producer*) How is temperature monitored and logged in your facility and in shipment? (ex: do you use a

TempTale or similar product to track temperatures? *(Wholesale, Food Retail, Restaurant*) How is temperature monitored and logged on truck? (*Freight Carrier)*

Do practices differ during summer months when Vibrio control plans are in effect? (*Producer*)

Where in your facility or during shipping is temperature difficult to maintain? *(Wholesale, Food Retail, Restaurant*) How can temperature control be improved during harvest and storage (*Producer*) or the distribution process? (*Wholesale)*

Where do you keep oyster tags? (*Food Retail, Restaurant*)

Do you use (or have you considered using) digital tags (QR codes or barcodes)? (*Producer, Wholesale, Food Retail, Restaurant*)

Have you ever been involved in a product recall or foodborne disease outbreak? Can you explain what happened? (*Producer, Freight Carrier, Wholesale, Food Retail, Restaurant*)

<u>Part E. Challenges and Opportunities</u>

Where do you see your business in 5 years? Are there any additional products or services would you like to add to your business? (*Producer, Wholesale, Food Retail, Restaurant*)

What are the biggest challenges for you in operating your business? Why? (*Producer, Wholesale, Food Retail, Restaurant*)

Table A.1. Average oyster temperature ± standard deviation for companies in the Washington State and Chesapeake Bay oyster supply chains (in Celsius and Farenhiet). P value for t-tests comparing each group. Samples sizes reported in Table A.2.

Company type [c]	Washington	Chesapeake Bay	P-value
Producer	3.2 ± 2.3 °C	6.6 ± 2.6 °C	< 0.0001
Wholesale	4.2 ± 3.0 °C	4.1 ± 1.2 °C	ns
Food retail/ Restaurant	4.3 ± 2.6 °C	3.8 ± 1.9 °C	ns
Freight carrier	4.1 ± 2.8 °C	5.0 ± 2.8 °C	0.0003
Total	3.9 ± 2.7 °C	5.0 ± 2.5 °C	< 0.0001

Company type [c]	Washington	Chesapeake Bay	P-value
Producer	38 ± 4 °F	44 ± 5 °F	< 0.0001
Wholesale	40 ± 5 °F	39 ± 2°F	ns
Food retail/ Restaurant	40 ± 5 °F	39 ± 3°F	ns
Freight carrier	40 ± 5 °F	41 ± 5 °F	0.0003
Total	39 ± 5 °F	41 ± 5 °F	< 0.0001

Table A.2. Percent of shipments with internal oyster temperatures above NSSP temperature criterium of 10 °C (50 °F)[a] (n)

Supply Chain	Washington State	Chesapeake Bay	Total
By Shipment [b]			
Domestic	15% (48)	17% (41)	16% (89)
International	100% (2)	-- (0)	100% (2)
Total	18% (50)	17% (41)	18% (91)
By Company type [c]			
Producer	2% (50)	5% (41)	4% (91)
Wholesale	12% (34)	0% (32)	6% (66)
Food retail / Restaurant	0% (30)	3% (34)	2% (64)
Freight carrier			
All freight carriers	8% (123)	6% (69)	7% (192)
Air freight	35% (17)	-- (0)	35% (17)
Ground freight	4% (84)	6% (66)	5% (150)
Freight forwarder	7% (14)	-- (0)	7% (14)
Direct-to-consumer	0% (8)	0% (3)	0% (11)
Total	6% (237)	3% (175)	5% (412)

[a] We categorized samples as over the criterium if they were above 10 °C (50 °F) for one hour or more.
[b] A shipment is a box or bag of oysters sent to a customer through a supply chain. There were 91 shipments with usable data in this study.
[c] There were 412 handlings of shipments in the study, and many companies handled multiple shipments during the study.

Table A.3. Percent of shipments with internal oyster temperatures below 1.67 °C (35 °F) [a] (n)

Supply Chain	Washington State	Chesapeake Bay	Total
By Shipment [b]			
Domestic	70% (48)	29% (41)	52% (89)
International	50% (2)	-- (0)	50% (2)
Total	72% (50)	29% (41)	53% (91)
By Company type [c]			
Producer	34% (50)	7% (41)	23% (91)
Wholesale	26% (34)	13% (32)	26% (66)
Food retail / restaurant	30% (30)	24% (34)	27% (62)
Freight carrier			
All freight carriers	34% (123)	6% (67)	21% (190)
Air freight	18% (17)	-- (0)	18% (17)
Ground freight	36% (84)	9% (64)	24% (148)
Freight forwarder	21% (14)	-- (0)	21% (14)
Direct-to-consumer	75% (8)	33% (3)	64% (11)
Total	32% (237)	12% (175)	24% (412)

[a] We categorized samples as over the criteria if they were below 1.7 °C (35 °F) for one hour or more.
[b] A shipment is a box or bag of oysters sent to a customer through a supply chain. There were 91 shipments with usable data in this study.
[c] There were 412 handlings of shipments in the study, and many companies handled multiple shipments during the study.

Comparing Vibrio Control Plan (VCP) months vs non-VCP months. We explored differences in product temperature between Vibrio Control Plan months (June - September) versus a non- Vibrio Control Plan month (March). We hypothesized that products under temperature control would maintain a similar internal oyster temperature regardless of the season. We found instead that producers and freight carriers maintained oyster boxes at elevated temperatures in Vibrio Control Plan months compared to a non- Vibrio Control Plan month ($p_{producer} = 0.001$; $p_{freight} = 0.001$), which led to higher internal oyster temperatures in Vibrio Control Plan months for producers and freight carriers ($p_{producer} = 0.007$; $p_{freight} < 0.0001$). (For producers, this statistical test only compares products under temperature control.) For wholesalers and wholesale delivery to retail/restaurants, the box temperature did not differ between Vibrio Control Plan months and a non-Vibrio Control Plan month. However, wholesalers did have elevated internal oyster temperatures in Vibrio Control Plan months compared to a non-Vibrio Control Plan month ($p = 0.02$), which appears to be a spill-over effect of higher internal oyster temperatures starting with producers and freight carriers. These effects wash out by the time the product reaches the food retailers and restaurants because there were no significant differences in internal oyster temperature or box temperature between Vibrio Control Plan months and non-Vibrio Control Plan month at food retailers and restaurants.

Table A4. Two tailed T-test comparing internal oyster temperature and environment temperature between groups in Vibrio Control Plan (VCP) months vs non-VCP months

Group	Internal oyster temperature (VCP vs non VCP months)	Environment temperature (VCP vs non VCP months)
Producer	** [a]	***
Freight Carrier	****	***
Wholesale	*	ns
Wholesale delivery	**	ns
Retail/Restaurant	ns	ns

[a] p values: * <0.05; ** <0.01; *** < 0.001; **** < 0.0001

Table A5. Tukey's multiple comparison test comparing temperature in (A) oysters or (B) the environment by step of the supply chain for months with Vibrio control plans.

A) Oyster internal temperatures in Vibrio control plan months [a].

Group	Producer	Freight Carrier	Wholesale	Wholesale delivery	Retail/ Restaurant
Producer	-				
Freight Carrier	ns	-			
Wholesale	*** [c]	****	-		
Wholesale delivery	****	****	**	-	
Retail/Restaurant	****	****	ns	ns	-

B) Environment temperatures in Vibrio control plan months [a].

Group	Producer	Freight Carrier	Wholesale	Wholesale delivery	Retail/ Restaurant
Producer	-				
Freight Carrier	* [c]	-			
Wholesale	****	****	-		
Wholesale delivery	****	****	ns	-	
Retail/Restaurant	****	****	ns	ns	-

[a] based on n = 20 samples with complete data
[b] based on n = 21 samples with complete data
[c] p values: * <0.05; ** <0.01; *** < 0.001; **** < 0.0001

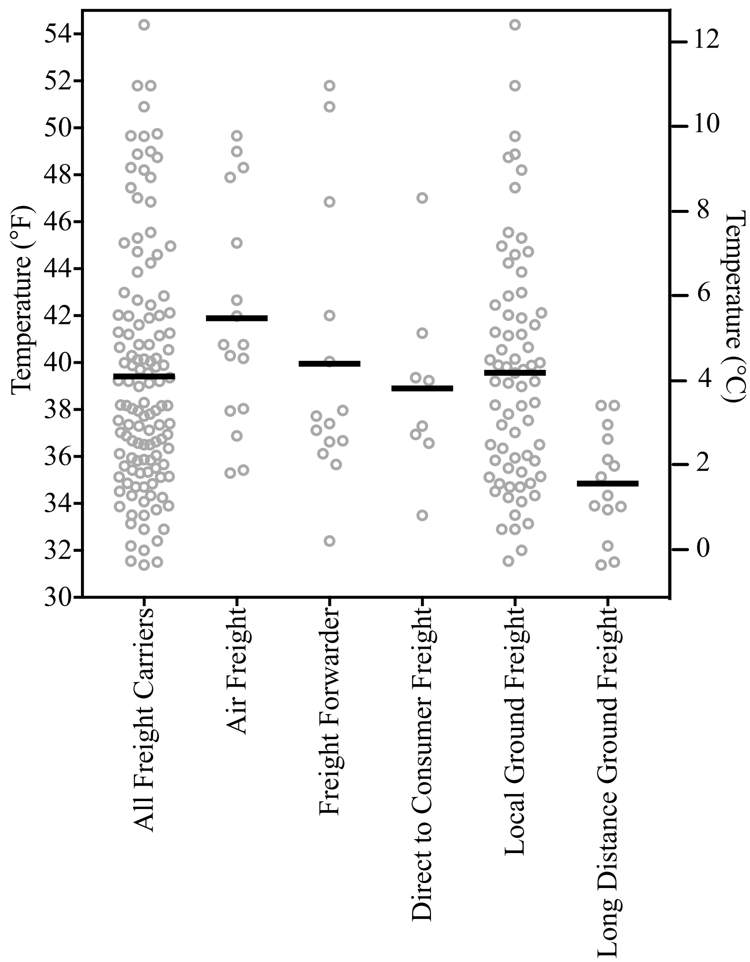

Figure A.1. Strip plot of average internal oyster temperature for Washington State oysters by freight carrier type. Y-axes are in °F and °C.

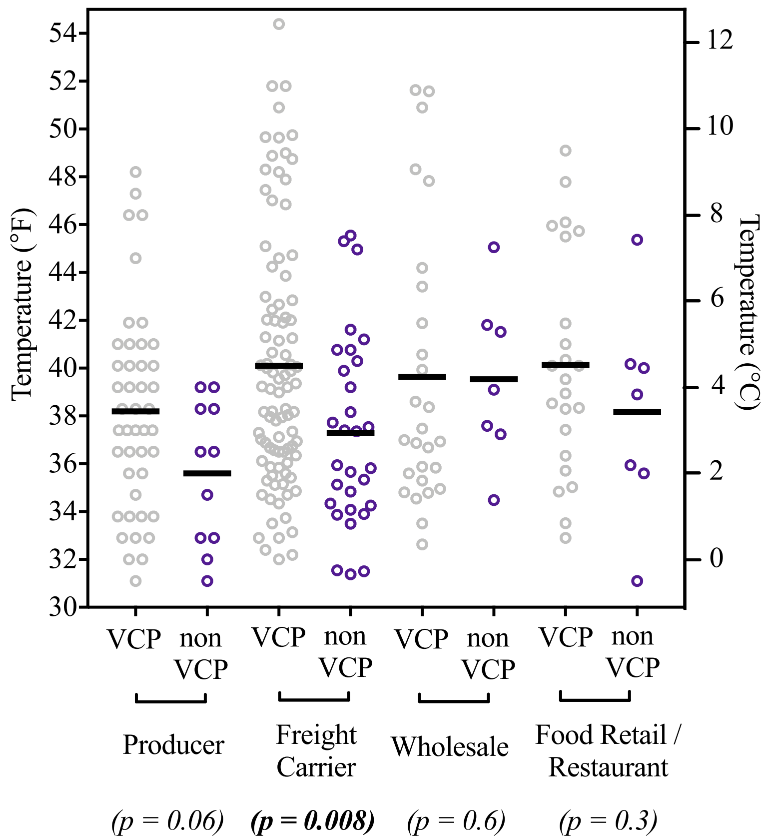

Figure A.2. Strip plot of average internal oyster temperature for Washington State oysters in *Vibrio* Control Plan months (VCP, grey) vs a non-VCP month (purple). Y-axes are in °F and °C.

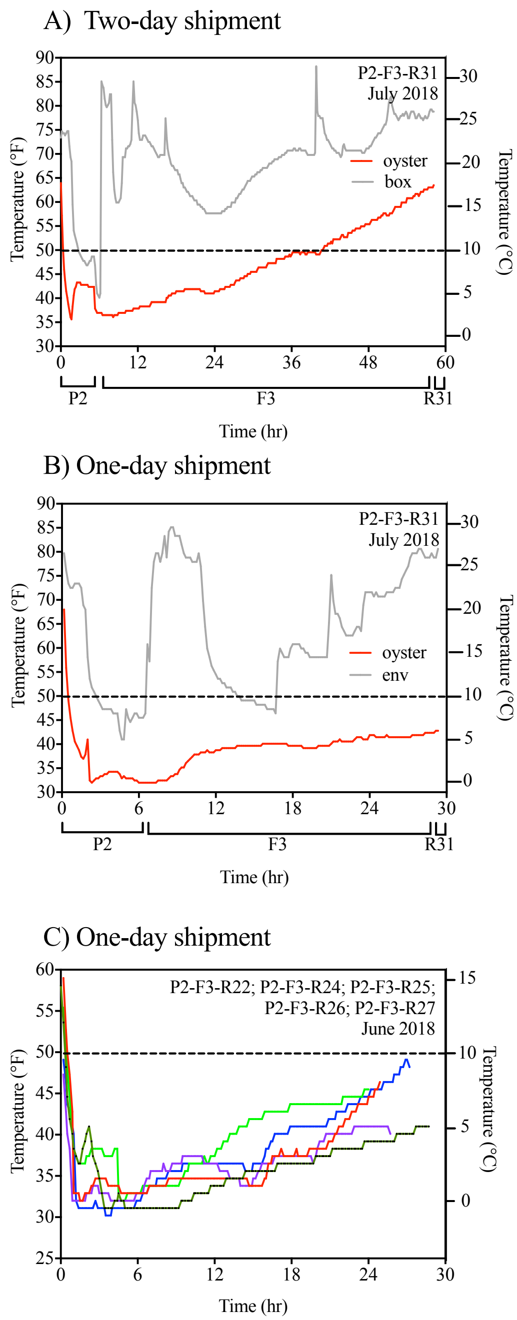

Figure A.3. Direct to consumer freight shipments. Two identical shipments from Washington State to a customer in California that arrived A) in two days and B) the next day. C) Five shipments that left a single producer in Washington State on the same day and shipped to customers in New York, Oregon, Pennsylvania, Tennessee, and Washington State. Shipments were in polystyrene-lined cardboard boxes with gel packs.

Temperature sensor pilot study. A pilot study was conducted in February 2017 where 34 sensors were deployed at the wholesale level. The purpose of the temperature sensor pilot study was to determine the variability in triplicate boxes shipped from wholesalers to retailers/restaurants. Sensors with usable data from the pilot are presented in Figure 1. The average standard deviations (grey error bars in Figure 1) were 0.62 for oyster sensors and 0.64 for sensors affixed to the outside of boxes. This finding suggests that replicate boxes provide greater accuracy than single boxes, however, the amount of variation between boxes was not large. After the pilot, wholesalers told us their preference was to add sensors to single boxes because many buyers do not order large enough volume to warrant delivery of triplicate boxes of the same product on the same day.

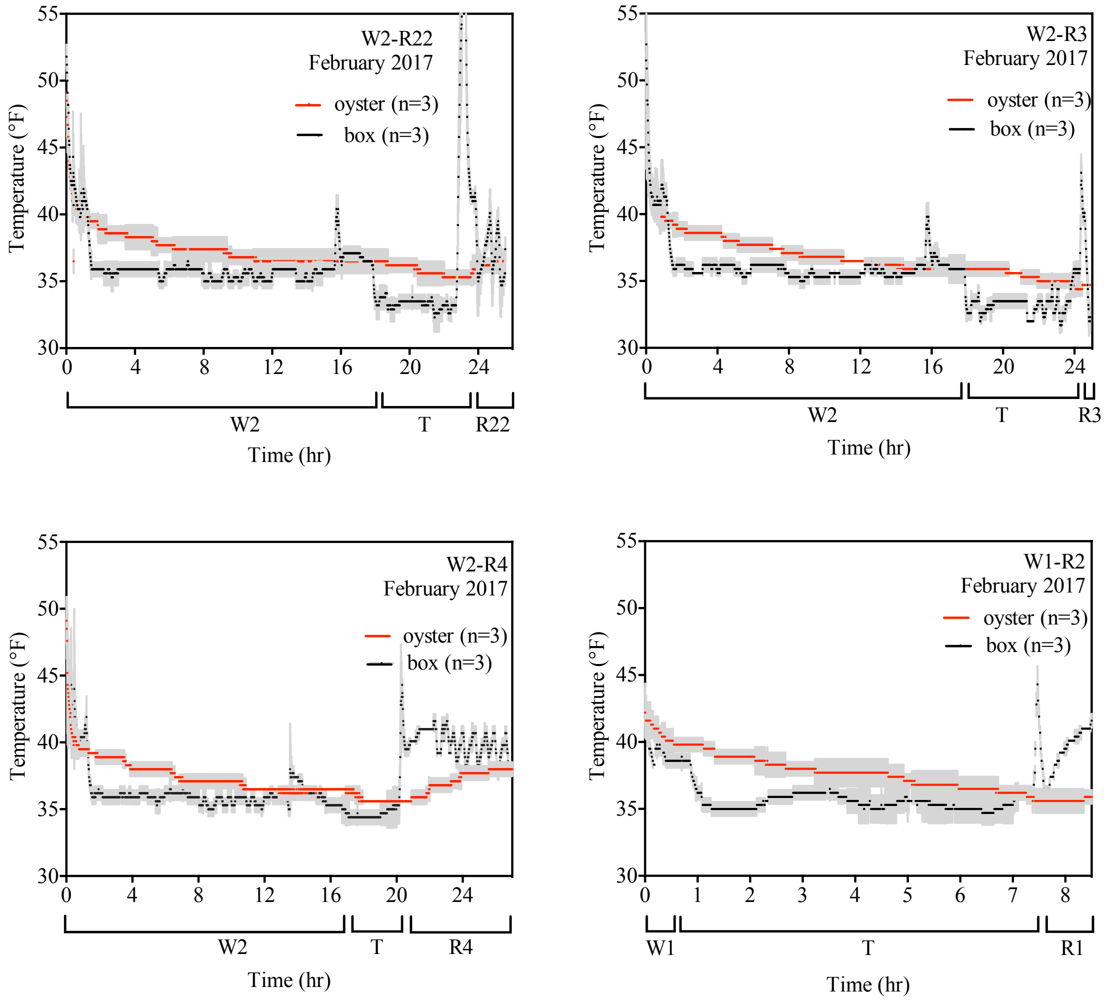

Figure A4. Pilot study to determine the variability in internal oyster temperature (red) and environment temperature (black) for triplicate 100-count boxes sent from wholesale to retail or restaurant customers. Grey bars indicate standard deviation (avg oyster st dev = 0.62, avg environment st dev = 0.64). The sensor sampling interval was 1 min. . P = producer; T = freight carrier (truck); W = wholesale; R = food retail or restaurant; C = consumer. The number following P, T, W, or R was assigned to each participant to provide anonymity