Received: 22 June 2024 | Revised: 27 January 2025 | Accepted: 6 February 2025

DOI: 10.1111/jwas.70005

APPLIED RESEARCH

Journal of the World Aquaculture Society Open Access | WORLD AQUACULTURE Society | WILEY

The National Regulatory Cost Burden on US aquaculture farms

Carole R. Engle[1] | Jonathan van Senten[2] | Shraddha Hegde[3] | Ganesh Kumar[4] | Charles Clark[2] | Noah Boldt[5] | Gary Fornshell[6] | Bobbi Hudson[7] | Eric J. Cassiano[8] | Matthew A. DiMaggio[8]

[1]Engle-Stone Aquatic$ LLC, Strasburg, Virginia, USA

[2]VA Seafood AREC, Virginia Tech University, Blacksburg, Virginia, USA

[3]Texas A&M University, College Station, Texas, USA

[4]Mississippi State University, Mississippi State, Mississippi, USA

[5]ESC, Inc., Arlington, Virginia, USA

[6]Aquaculture Results LLC, University of Idaho Extension, Moscow, Idaho, USA

[7]Pacific Shellfish Institute, Olympia, Washington, USA

[8]Tropical Aquaculture Laboratory, University of Florida, Moscow, Idaho, USA

Correspondence
Carole R. Engle, Engle-Stone Aquatic$ LLC, Strasburg, VA, 22657, USA.
Email: caroleengle2015@gmail.com

Funding information
Economic Research Service, Grant/Award Number: 58-60000-2-0122

Abstract

Many government regulations have improved environmental and social quality of life in the United States, but others have resulted in negative consequences that exceed their benefits to society. This study estimated the total annual cost of regulatory compliance and lost revenue for US aquaculture. The total annual regulatory cost was $196 million (in 2023 USD), which accounted for 9%–30% of total annual costs, one of the top five costs of aquaculture production. Regulatory costs result in disproportionately greater per-unit costs of production on smaller-scale farms. Total annual lost revenue was $807 million (36% of total sales value), which resulted from lost sales and thwarted expansion opportunities from regulatory actions that either closed

access to existing markets, forced reduced scales of production, or prevented attempts to expand production to meet existing demand for the farm's products. Accounting for multiplier effects, lost economic contributions were $1.4 billion annually, with >8000 jobs lost nationally from farms alone, not including associated supply chain partners. Well-designed regulations made use of best available science, participatory approaches to rule-making, sunset clauses for removal of outdated regulations, and market-based approaches. Pathways identified to improve regulatory efficiency included: (1) sunset clauses for each rule; (2) reward incentives (i.e., reduced testing frequency for farms with records of compliance) (3) standardized fish health testing requirements of sample size, farm-wide rather than lot testing, testing the most susceptible species/life stages; (4) non-lethal, multi-pathogen testing methods; (5) farm compensation for reverse externalities of avian predation; (6) appropriate risk management by experts to manage aquatic invasive species and pathogens; (7) training in aquaculture science, current farm practices, and appropriate, consistent, regulatory actions; (8) engagement with independent experts and producers throughout rule-making; (9) establishment of transparent appeals processes for farmers; (10) concurrent, not sequential review of permit requests by agencies; (11) long-term aquaculture literacy programs; and (12) an efficient, streamlined permitting and regulatory framework for mariculture.

KEYWORDS
aquaculture economics, aquaculture governance, regulations, regulatory costs, US aquaculture

1 | INTRODUCTION

Governments exist to create and enforce the rules necessary for an orderly society, protect its citizens, and promote general welfare. As part of general welfare in the United States, citizens expect a clean, healthy environment, safe food and drugs, and fair business and employment practices (Beales et al., 2017). There is little question that US federal and state regulations over time have resulted in improved air and water quality, safer highways and work environments, and improved public health, among other benefits (OMB, 2017, 2024).

Economic analyses of the effects of regulations on industries and the economy date back to seminal work by Stigler (1971) who provided a theoretical framework that subsequently led to robust research on the economics of

regulation. Various studies have identified clear benefits to society from regulatory action. For example, reductions in pollution from environmental regulations were found to be associated with increased annual earnings and worker productivity, presumably from improved health status (Chang et al., 2016; Currie & Walker, 2019; Isen et al., 2017; Zivin & Neidell, 2012). Such laws and subsequent compliance and enforcement rules, particularly those that have improved environmental and social quality, have been widely supported by the public.

Regulations developed without adequate attention to potential unintended consequences (referred to as "poorly designed regulations" by Beales et al., 2017), however, cause delays, result in excessive compliance costs, onerous paperwork, and reduce innovation and productivity (Porter & van der Linde, 1995; Executive Order 12866, 1993; OMB, 1997). The continuously increasing numbers of US regulations, 58% increase in pages in the Federal Register from 1976 to 2023 (Crews, 2023), with a 12% increase from 2022 to 2023 alone to 90,402 pages (Noe, 2016) has led to increased concern and greater research attention to its overall effects. Businesses that sell products for which demand is inelastic and for which there are few good substitutes may be able to pass increased costs from regulations through to customers, while businesses selling products with elastic demand into highly competitive markets with more similar products may not be able to pass the higher costs from regulations on to customers. There are economic consequences, however, even for those businesses and industries that can pass increased costs from regulations on to customers. For example, in the power-generating sector, Curtis (2018) found that a cap-and-trade program designed to reduce emissions resulted in increased costs that were passed through to manufacturing companies that then decreased employment by 1.3% overall, and by 4.8% in energy-intensive industries. Increased consumer prices that result from increased regulatory costs on businesses frequently affect low-income households to a greater extent than higher-income households (Thomas, 2012), and contribute to greater income inequality (Chambers et al., 2018). For industries that cannot pass increased regulatory costs on to consumers, increased regulatory costs often have substantial effects. Bailey and Thomas (2017) found that the increased costs in more heavily regulated industries resulted in greater proportions of smaller firms exiting the industry, fewer firms entering, and slower employment growth than in less regulated industries.

Disagreement over the relative costs and benefits of regulations arises primarily from variability in the development and implementation of the many specific compliance provisions of rules developed to enforce the laws passed by federal and state lawmakers (Beales et al., 2017). As one example, few regulations have sunset clauses, such that each new regulation adds to an ever-increasing number of total regulations that compounds the complexity of the overall regulatory framework, increasing inefficiencies, and reducing innovation (Mandel & Carew, 2013). Overall, the growing number and complexity of regulations in the United States have contributed to slower economic growth (Dawson & Seater, 2013). Highly prescriptive regulations generally constrain development but are especially restrictive for businesses developed with new technologies (Oster & Quiglay, 1977), such as the rapidly evolving technologies in aquaculture (Asche & Smith, 2018; Osmundsen et al., 2017).

Evidence of an overly complex and redundant regulatory framework in the United States has grown for agriculture (Antle, 2000; Hurley & Noel, 2006; Kaplan et al., 2004; Metcalfe, 2002) and specifically for aquaculture (Engle & Stone, 2013; Knapp & Rubino, 2016; Rubino, 2022; Wirth & Luzar, 2001). The 2012 Executive Order, "Identifying and Reducing Regulatory Burdens" acknowledged the regulatory compliance burden in the United States (Executive Order No. 13610, 2012). The US regulatory framework is further complicated by the rights of individual states to set policies and rules as they choose so long as they meet or exceed compliance criteria set by the corresponding federal agency. The combination of increased regulations from federal agencies in each of the 50 states increased the reported regulatory compliance burden to "billions of dollars in regulatory costs and tens of millions of hours in annual paperwork burdens" in 2012 (Executive Order No. 13610, 2012), that further increased to $3.1 trillion in 2022 (Crain & Crain, 2023). Additional complexity to the US regulatory framework accrues from the authority of local towns, counties, and districts to pass ordinances and enforce those provisions in addition to required state and federal laws and regulations.

US aquaculture contributed $4 billion in total economic output and 22,000 jobs in 2022 from the farm sector alone, not including contributions from supply chain partners of aquaculture farms (Kumar et al., 2024). The economic contributions of aquaculture are especially important because most aquaculture production occurs in rural areas with few economic and employment opportunities (Engle & van Senten, 2022; Krause et al., 2015; Peel & Lloyd, 2008). Aquaculture supports a high percentage of sectors throughout the economy and has created new businesses and supply chains (Botta et al., 2021; Dicks, 1996; Hegde et al., 2022; Kaliba et al., 2004; Kaliba & Engle, 2004). Despite its economic importance in many regions of the US, the rapidly increasing regulatory burden has resulted in much slower growth of aquaculture in the United States and the European Union as compared with many other countries (Abate et al., 2016; Duff et al., 2003; Engle & Stone, 2013; Farquhar et al., 2017; Osmundsen et al., 2017; Thunberg et al., 1994). Stringent and redundant regulations have been reported to have reduced aquaculture farm productivity (Duff et al., 2003; Lockwood, 2017), and constrained future growth (Farquhar et al., 2017; Kite-Powell et al., 2013). Equally important is that the United States is the largest importer of seafood in the world (FAO, 2024), and the resulting trade deficit reached a record high of $20.3 billion in 2023 (Davis, 2024). Other unintended consequences of the US regulatory system include: (1) negative effects on food security (Rexroad et al., 2021) resulting from increased volumes of imports in response to the higher US production costs that decrease competitiveness with international businesses not required to pay similar environmental regulatory costs; (2) displacing negative environmental externalities to other parts of the planet with less stringent and rigorous environmental regulations and enforcement (Froehlich et al., 2020; Helvey et al., 2017); (3) reduced economic contributions and employment opportunities in US rural areas because farms are restricted from expansion to optimal scales of production; and (4) lack of development of a robust marine finfish sector.

Various studies have highlighted the disparity between the stringency of regulations and enforcement in the United States and European Union as compared with that of developing nations that supply large percentages of seafood products to the United States and European Union (Abate et al., 2016). Abate et al. (2016) defined "stringency of regulations and enforcement" based on combinations of input-oriented and output/outcome-oriented metrics to construct a stringency index following Walter and Ugelow (1979) that accounted for both regulation and its enforcement by country. There is ample evidence that US aquaculture products are produced sustainably (for examples of several summaries, see Naylor et al., 2021; Zajicek et al., 2021; Seafood Watch, 2020a, 2020b, 2022, 2023a, 2023b; Garlock et al., 2024), with US channel catfish, US rainbow trout, and clams (globally) rated as "Super Green". However, governance of aquaculture through regulation is needed in developing countries to manage and reduce negative impacts on the environment (Genschick, 2011; Herbeck et al., 2020), human health (Reverter et al., 2020; Rico et al., 2013), and on livelihoods (Primavera, 2006; Wu et al., 2017).

The first of nine formal farm-level economic surveys measuring regulatory costs on US aquaculture farms was initiated in 2014 (van Senten & Engle, 2017). Overall, national surveys were conducted of baitfish/sportfish (van Senten & Engle, 2017), salmonids (Engle et al., 2019), catfish (Hegde et al., 2023), tilapia (Engle et al., 2023), hybrid striped bass (Engle & van Senten, 2023), and redfish (Engle & van Senten, 2023). Distinct regional surveys were conducted of Pacific Coast shellfish (van Senten et al., 2020); Atlantic Coast shellfish (van Senten et al., in preparation); and a statewide survey was conducted of ornamental aquaculture farms in Florida (Boldt et al., 2023). Results of the Florida ornamental survey provided a measure of the value of and need for a pond preparation chemical for the nonfoodfish raised on ornamental farms that contributed to the approval of a Special Local Needs permit (Tropical Aquaculture Laboratory, 2024) and the subsequent positive impacts on the sector. The Florida example illustrates the value of measuring the economic effects of regulations on US aquaculture farms.

The overall goal of this study was to analyze the total effects of the regulatory framework across US aquaculture. Specific objectives were to: (a) estimate the total cost of regulatory compliance across all US aquaculture; (b) estimate the total lost revenue resulting from regulatory decisions in the United States.; (c) compare and contrast economic effects of the US regulatory framework across major sectors of US aquaculture; and (d) identify characteristics of well-designed regulations from the research literature.

2 | METHODS

Detailed survey methodologies of nine major sectors of US aquaculture are available for baitfish/sportfish (van Senten & Engle, 2017), salmonids (Engle et al., 2019), catfish (Hegde et al., 2023), tilapia (Engle et al., 2023), hybrid striped bass (Engle & van Senten, 2023), redfish (Engle & van Senten, 2023), Pacific Coast shellfish (van Senten et al., 2020); Atlantic Coast shellfish (van Senten et al., in preparation), and ornamental aquaculture farms in Florida (Boldt et al., 2023). Briefly, each survey was designed as a census for which every attempt was made to contact all known producers nationally (for catfish, baitfish/sportfish, salmonids, tilapia, hybrid striped bass, and redfish), within specified regions (for Pacific and Atlantic Coast shellfish), or within the state with the greatest concentration of farms (Florida ornamentals). The choice of a census, rather than a sampling approach, was based on preliminary evidence of substantial variations in regulatory effects across states and from farm to farm. Each survey represented a snapshot in time for each sector, with farmers asked to respond based on the regulatory costs and market effects for the year preceding the survey.

Most interviews were conducted in person, with a small percentage conducted by telephone. Interviews lasted from approximately 1 hour to more than 3 h each. The survey instruments developed were reviewed for content validity by industry experts, extension personnel who work closely with each relevant sector and knowledgeable researchers, and were revised accordingly. Pre-tests with producers were conducted for each survey to ensure that questions were worded clearly, used terminology commonly employed in each farming sector, and to ensure that questions were unambiguous. Coverage rates were generally high with seven of the sectors surveyed covering 63% to 99.8% of the value of aquaculture in that sector (Table 1). The lowest coverage rates were those of Atlantic Coast shellfish (31%) and hybrid striped bass (37%). Response rates ranged from 6% (Atlantic Coast shellfish) to 89% (redfish).

Farm business data are confidential, and standard procedures were followed to protect the confidentiality of each survey respondent. Observations were coded without individual identifying information, and only those individuals who were signatories to the confidentiality agreement for that sector had access to the data files. Data were reported in aggregate with categories selected to ensure that no individual farm data would be disclosed.

Data from the nine surveys were entered into a common spreadsheet, and cost and revenue data were adjusted to 2023 values using the Consumer Price Index (CPI) (US Bureau of Labor Statistics, 2024). Direct regulatory compliance costs were summed across all aquaculture sectors to obtain a total direct cost of regulatory compliance for the nine sectors. This value was adjusted for the overall national surveyed coverage rate of 77% of all US aquaculture (Table 1) to estimate the total national regulatory compliance burden. Total direct costs were further calculated as

TABLE 1 Coverage and response rates of regulatory cost surveys of major sectors of US aquaculture.

Sector	Response rate (%)	Respondents[a] (no.)	Coverage rate (%)	Reference
Catfish	17%	78	63%	Hegde et al. (2023)
Salmonids	63%	101	94.5%	Engle et al. (2019)
Pacific Coast shellfish	27%	48	74%	van Senten et al. (2020)
Atlantic Coast shellfish	6%	79	31%	van Senten et al. (in prep.)
Baitfish/sportfish	34%	60	74%	van Senten and Engle (2017)
Ornamentals	41%	30	82%	Boldt et al. (2023)
Tilapia	18%	24	75%	Engle et al. (2023)
Hybrid striped bass	35%	11	37%	Engle and van Senten (2024)
Redfish	89%	8	99.8%	Engle and van Senten (2024)
Total coverage of US aquaculture 77%				

Note: Percent of total production values.
[a]Completed responses.

the mean regulatory cost per farm and as a percent of total farm costs. Regulatory compliance costs were compared across aquaculture sectors. Per-unit regulatory costs were calculated as $/kg for foodfish sectors (i.e., catfish, salmonids, tilapia, hybrid striped bass, redfish), whereas per-unit costs for baitfish/sportfish, ornamentals, and shellfish were reported as a percent of total sales because products in these sectors are not sold by weight. Regulatory compliance costs were further calculated as the percentage contribution to fixed and variable costs.

The US regulatory framework includes laws for which rules are promulgated to regulate environmental quality, the safety of the food supply, working conditions for farm employees, and the safety of the transportation system. Survey data were disaggregated into various regulatory categories to compare the magnitude of each for aquaculture farms. Regulatory categories identified in the survey datasets included: environmental management, legal, labor, food safety, transportation, aquatic animal health, and taxes. The environmental management category was subdivided into avian predator management, effluent discharge management, water rights and access, effects on coastal ecosystems, non-native species/gamefish status, and storage and disposal of chemicals and wastes. Regulations related to immigration were included in the labor category along with worker safety requirements. Most sectors of US aquaculture reported regulations in these various regulatory categories, although the degree of effect varied by sector, region, and farm. A few exceptions included non-foodfish sectors (baitfish, sportfish, and ornamentals) for which food safety regulations were not applicable and farms raising freshwater species not subject to coastal ecosystem and use regulations.

The regulatory costs reported in the surveys included different types of costs. To further understand the effects on farm businesses, total regulatory costs were disaggregated by cost types that included: permits and licenses, management and labor, capital for regulatory compliance, insurance, legal and professional services (i.e., environmental consultants, engineers), taxes, and direct costs other than permits and licenses.

Regulatory actions on US aquaculture farms resulted in lost revenues in addition to increased costs. Lost revenue reported from US aquaculture businesses took several forms; thus, the values of lost revenues were disaggregated into the component categories of the value of markets lost from regulatory decisions, the value of lost production as a result of regulatory actions, and the value of opportunities lost when expansion attempts were thwarted. Lost revenues were summed across all surveys, adjusted to 2023 dollars using the CPI, and adjusted for national coverage to obtain an estimate of total national lost revenue. Lost revenue from regulatory action was compared across aquaculture sectors.

Farm size effects of regulatory costs were examined by disaggregating survey data by farm size categories identified through examination of the structure of farm sizes in each sector. Farm size structures varied across the diverse sectors of US aquaculture and reflect differing supply chains, target markets, and the evolution of each sector. Specific size categories for each sector are presented in the Results section on scale effects and in the detailed publications from sector-specific surveys. There were insufficient numbers of observations of hybrid striped bass and redfish farms to group into size categories, but scale effects were reported at industry levels to preserve confidentiality.

The study also sought to identify economically efficient pathways for reducing the regulatory compliance burden in US aquaculture. A review of the research literature on the effects of regulations identified characteristics of well-designed regulations. The characteristics identified were used in conjunction with survey recommendations for reducing the regulatory compliance burden to suggest pathways for more efficient (i.e., less costly) regulation of US aquaculture.

3 | RESULTS

3.1 | Ranking of regulations as compared with other challenges of US aquaculture farms

Respondents across all nine surveys were asked to list and rank the greatest problems and challenges on their farms. Overall, more than half (54%) reported that regulations were either the top or the second-greatest problem faced,

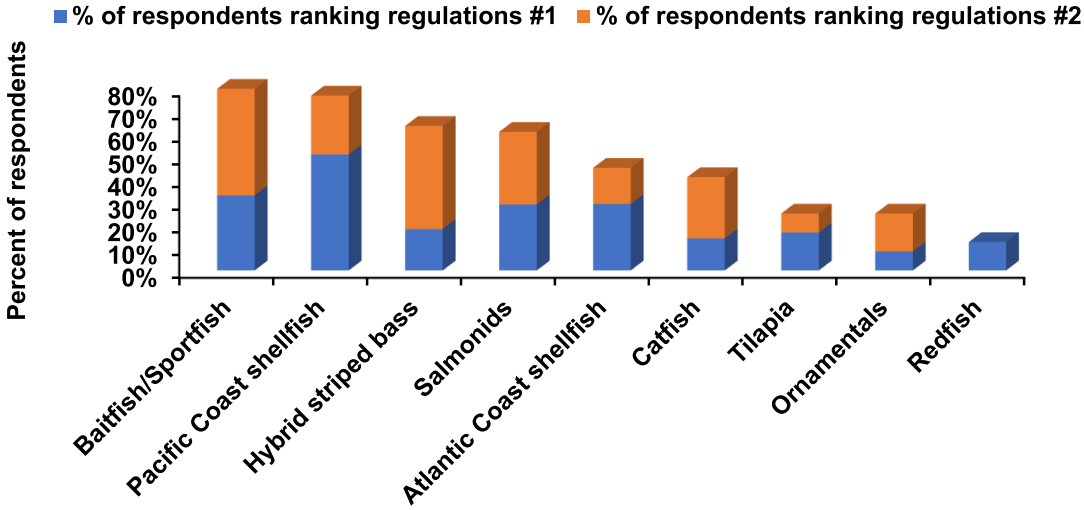

FIGURE 1 Percentage of respondents ranking regulations as the no. 1 or no. 2 most problematic, by aquaculture sector.

but percentages varied across sectors (Figure 1). Greater percentages of baitfish/sportfish, Pacific Coast shellfish, hybrid striped bass, and salmonid producers reported regulations being their top or second-greatest problem, followed by respondents to the Atlantic Coast shellfish, catfish, tilapia, and ornamental surveys. More than half (51%) of Pacific Coast shellfish producers indicated that regulations were their primary challenge. A third (33%) of baitfish/sportfish producers also ranked regulations as their top challenge, followed by 29% of salmonid and Atlantic Coast shellfish respondents, and 13% of redfish respondents. While other sectors faced top challenges other than regulations, 45% of hybrid striped bass, and 27% of catfish respondents reported that regulations were their second-greatest challenge.

The specific regulations that were most problematic varied by aquaculture sector. For Pacific Coast shellfish, the US Army Corps of Engineers actions with respect to shellfish permitting dominated the list. Shellfish growers on the Atlantic Coast reported that the most problematic were regulatory actions related to shellfish sanitation such as harvesting closures when contaminants or pathogens were found in waters where shellfish were being grown. The most problematic regulations for baitfish/sportfish and trout producers who sell into recreational markets were the permits required by other states where customers were located, to allow fish to be imported into those states. Effluent discharge and the frequency of effluent testing were the greatest problems for tilapia, redfish, and salmonid producers who primarily sell foodfish. The greatest problem for catfish and the second-greatest problem for redfish and hybrid striped bass producers was that of managing avian predators on their farms, many of which are protected under the Migratory Bird Treaty Act. Tilapia producers mentioned issues with shipping and trucking regulations to deliver live fish to markets. Hybrid striped bass producers experienced high costs related to regulation of farming gamefish species. For ornamental producers, regulation of interstate and international shipping of live products was the greatest problem, followed closely by access to water and approval of non-foodfish use of drugs and chemicals used by international competitors.

3.2 | Regulatory cost burden on US aquaculture farms

The total regulatory cost burden across US aquaculture farms (adjusted to 2023 values) was $196 million annually (Table 2). The average regulatory cost per farm ranged from $29,128 to $450,564 per farm per year. The sectors

TABLE 2 Total regulatory cost of US aquaculture, average farm costs, percentages of regulatory costs of total costs, and percent of regulatory costs that were fixed costs, adjusted to 2023 values.

Sector	Total regulatory cost ($)	Mean farm regulatory cost $/farm	Regulatory costs as % of total costs %	Percent of regulatory costs that are fixed costs %
Catfish	55,784,158	450,564	9%	63%
Salmonids	36,225,033	338,937	13%	74%
Pacific Coast shellfish	20,790,436	320,519	30%	72%
Baitfish/sportfish	10,403,837	128,314	17%	78%
Atlantic Coast shellfish	7,423,041	29,128	9%	65%
Ornamentals	6,417,723	175,418	26%	87%
Tilapia	6,168,518	192,766	18%	79%
Hybrid striped bass	5,340,646	179,640	22%	84%
Redfish	2,626,606	328,326	15%	82%
TOTAL	151,179,999			
Adjusted for coverage	196,337,661			

with the greatest total regulatory costs were the largest sectors of US aquaculture, including catfish, salmonids, and Pacific Coast shellfish. The sectors with the greatest mean farm regulatory costs were catfish and salmonids, followed by redfish, Pacific Coast shellfish, tilapia, hybrid striped bass, and ornamentals, with the mean farm regulatory costs substantially lower for Atlantic Coast shellfish farms. On-farm regulatory compliance costs ranged from 9% of total farm costs to 30%, making on-farm regulatory compliance a major cost of production for many sectors. The catfish sector had one of the lowest percentages of regulatory compliance costs relative to total costs, but as the largest sector of US aquaculture, still ranked first in the total regulatory compliance burden.

Regulatory costs in foodfish sectors accounted for substantial proportions of the per-unit cost ($/kg) of foodfish. Per kg, the greatest regulatory compliance cost on foodfish farms was for hybrid striped bass, followed by tilapia, redfish, salmonids, and catfish (Figure 2). Of the sectors that do not sell products by weight, regulatory costs were 12% of total sales for ornamental farms, 11% for baitfish/sportfish, 9% for Pacific Coast shellfish, and 4% for Atlantic Coast shellfish farms (Figure 3).

Environmental management regulations resulted in the greatest proportion (40%) of regulatory costs on US aquaculture farms (Figure 4). The second-greatest regulatory costs were taxes (19%), followed by labor (15%), legal (11%), food safety (8%), transportation (5%), and aquatic animal health (2%). Of the various environmental management regulatory costs, managing avian predators accounted for 51%, followed by effluent discharge testing (26%), coastal ecosystem regulations (14%), water rights and access (7%), use of non-native or game species (1%), and finally chemical storage, waste disposal, and other on-farm requirements (1%) (Figure 5). Specific examples of environmental management regulatory costs include: (1) restrictions on shellfish farming related to potential ecosystem effects on eelgrass or submerged aquatic vegetation; (2) requirements for retail customers to file reports for each purchase of a farmed fish classified as gamefish; and (3) delays in issuing depredation permits for avian predators that resulted in greater fish losses.

The greatest portion of aquatic animal health regulatory costs resulted from inspections to prove health status. For salmonids, the greater portion of the cost of fish health inspections was the laboratory testing cost (Engle et al., 2021), whereas for baitfish/sportfish, the cost of sampling the 8-ha earthen ponds for collection of fish to be tested for proof of health status was the greatest fish health cost (van Senten & Engle, 2017). Fish health testing

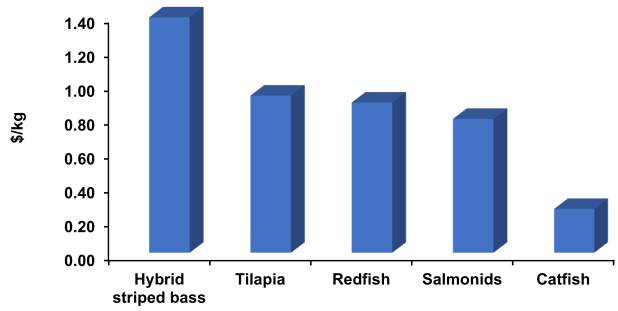

FIGURE 2 Regulatory compliance costs as $/kg of foodfish produced by sector, in 2023 $.

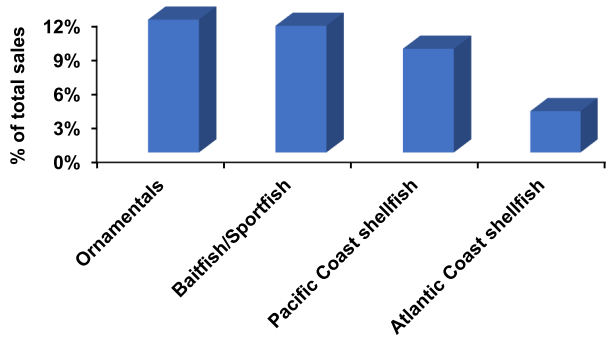

FIGURE 3 Regulatory compliance costs as percent of sales, ornamentals, baitfish/sportfish, and shellfish. Values in percent of total sales.

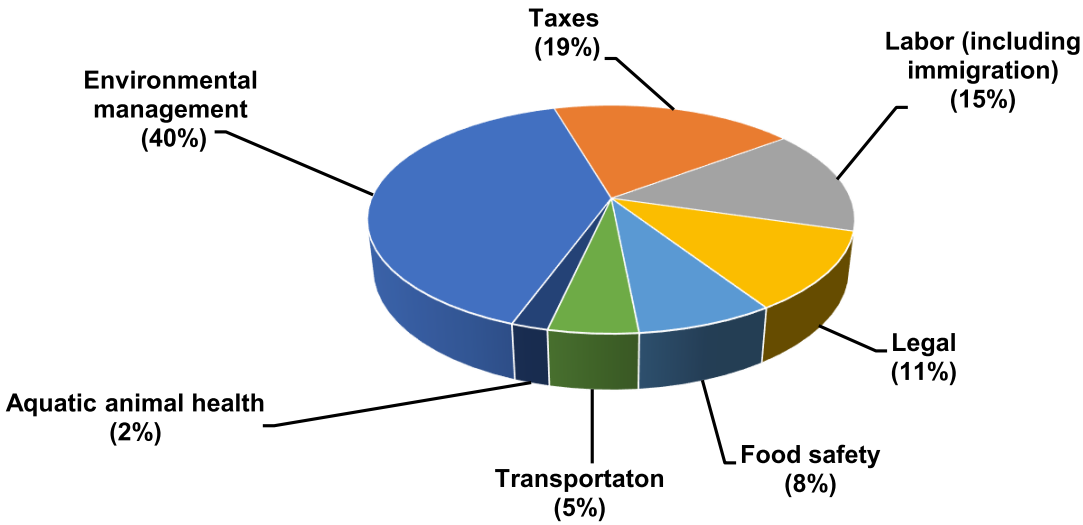

FIGURE 4 Total US regulatory costs by regulatory category, all sectors combined. Values in percentage of total regulatory cost.

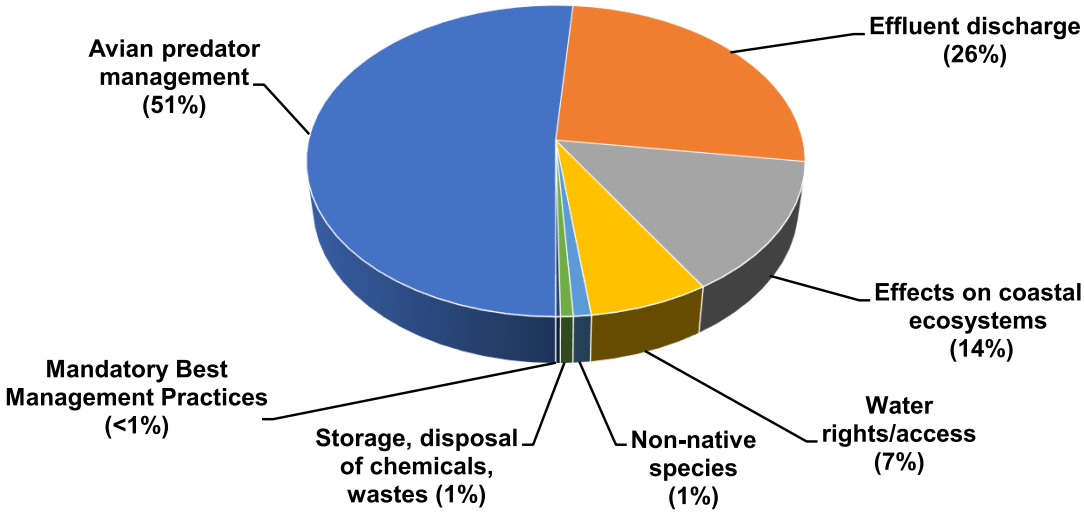

FIGURE 5 Environmental management costs by category of environmental regulation. Values in percentage of total environmental management costs.

costs increased mostly with the number of tests to be conducted (Engle et al., 2021). Testing costs included the management and labor costs of preparations to sample fish for testing, veterinarian fees, laboratory testing, shipping, and the value of fish sacrificed. Costs increased exponentially with the number of species, size and age classes, and lots that regulators required to be tested.

The costs of labor regulations were primarily those of contracting attorneys to navigate the visa process to hire guest workers (foreign workers with legal US work permits). Legal costs were mostly for legal counsel required for regulatory actions, but included the costs of shellfish permits that resulted in additional legal fees stemming from lengthy delays across multiple agencies. Food safety regulatory costs included the time spent on recording and monitoring temperatures for harvesting and transporting shellfish along with the time required to submit temperature data to multiple agencies in different formats.

The greatest cost category of on-farm regulatory compliance was that of direct costs other than the cost of the permit alone, which accounted for 28% of all regulatory compliance costs (Figure 6). Such direct costs include expenses for employee training, consultants to conduct required surveys, and laboratory testing for effluent discharge and fish health status required by states to import fish from another state, among other expenses. The second-greatest cost of regulatory compliance was for time spent by management and labor on compliance activities and reporting, at 25% of total regulatory costs. Survey respondents reported spending substantial amounts of time attempting to identify changes in regulatory requirements of all states where customers were located. Frequent turnover of agency personnel charged with managing state-level import permits often resulted in extensive delays. Insurance accounted for 12% of total regulatory costs and included worker's compensation that is required for larger businesses as well as vehicle insurance for farm vehicles and fish hauling trucks in addition to liability insurance for the farm. Capital costs associated with required investment in new equipment, facilities, or modifications to existing facilities accounted for 10% of total regulatory costs. Capital costs were measured as the annual interest on the investment in capital assets required for compliance. Other, often unexpected, changes on farms from regulatory compliance accounted for 6% of total regulatory costs. These included changes in classification of shellfish leasing sites and regulatory requirements that were changed when new agency staff were hired. Legal and other professional services that included counsel for legal action or engineering and environmental consultants accounted for 3% of total regulatory costs, while the permits themselves accounted for only 2% of the total regulatory compliance burden on US aquaculture farms.

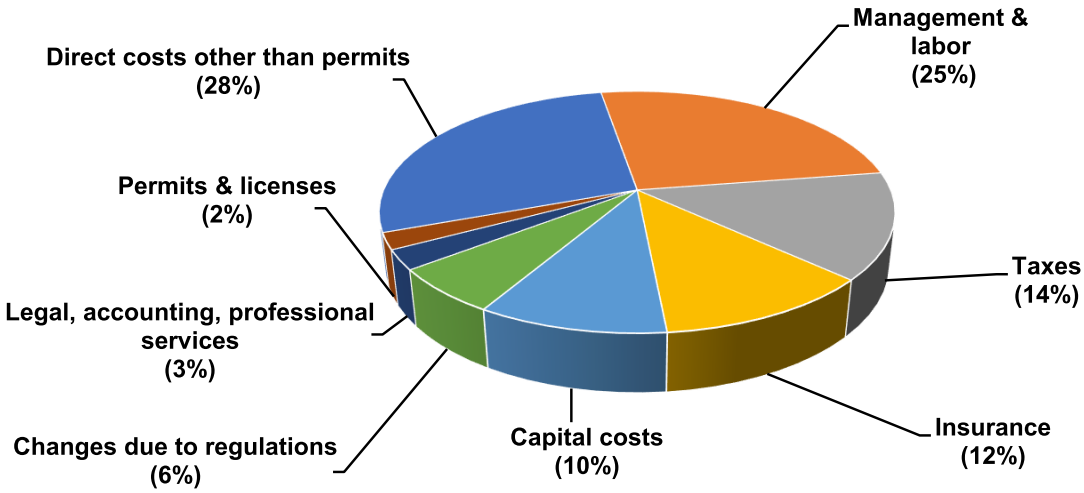

FIGURE 6 General categories of costs incurred from regulatory compliance aggregated across all US aquaculture. Values in percent of total regulatory cost.

3.3 | Lost revenue from regulations on US aquaculture farms

The total value of the revenue lost annually from regulations was $807 million (adjusted for national coverage, in 2023 USD) (Table 3). All sectors of US aquaculture interviewed reported lost revenue as a result of regulations (Figure 7). Lost revenue values were related to some degree to the overall size of the sector, with the greatest amount of lost revenue measured in the Pacific Coast shellfish sector. Abrupt changes in the nature of the permits required in Washington, the largest mollusk-producing state in the United States (USDA-NASS, 2024), accounted for much of the lost revenue in the Pacific Coast shellfish sector, although California producers also reported fairly high levels of lost revenue. The lost revenue per farm in finfish sectors ranged from nearly $500,000 to $4 million per farm and from $0.12 to $5.42/kg of finfish produced (data not shown). As a percent of total sales revenue, the revenue lost from Pacific Coast shellfish farms was 159% of total sales revenue, followed by 42% for ornamentals, 24% for baitfish, and only 5% for Atlantic Coast shellfish. Twenty-nine percent of Atlantic Coast shellfish respondents reported lost sales opportunities, but did not provide an estimate of those potential sales; thus, the 5% value of lost revenue as a percent of total sales may be underestimated.

More than half (53%) of the lost revenue reported resulted from lost sales opportunities (Figure 8). An additional 32% of the lost revenue was from markets that were closed to aquaculture producers through regulatory actions, and another 15% from production lost by regulatory actions that forced producers to either take units out of production or otherwise restrict production levels. Overall, the lost revenue values estimated indicated a demand of $807 million for US aquaculture products that was lost because of regulations. Compared with the 2023 value of US aquaculture sales of $2270 million (USDA-NASS, 2024), US aquaculture could have been 36% greater if regulations had not constrained production and sales of the sector. Lost sales of $870 million equate to lost total economic output of $1.4 billion based on the national multiplier reported by Kumar et al. (2024) and more than 8000 jobs nationally.

3.4 | Differential scale effects of regulatory costs on US aquaculture farms

The effects of regulations differed by farm size for all sectors analyzed other than hybrid striped bass (Figure 9). There were sufficient numbers of observations to identify clusters of farm-size groupings for all but two sectors (hybrid striped bass and redfish).

TABLE 3 Lost revenue from regulations, adjusted to 2023 values.

Sector	Total lost revenue ($)	Lost markets $	Lost opportunities and thwarted expansion $	Lost production $
Pacific Coast shellfish	360,580,257	142,038,412	218,541,845	–
Salmonids	66,691,213	9,008,963	50,945,840	6,736,409
Catfish	41,560,703	4,987,284	2,493,642	34,079,777
Tilapia	38,423,032	–	33,428,824	4,994,209
Hybrid striped bass	36,859,870	7,406,231	565,895	28,887,744
Ornamentals	29,078,826	–	14,539,413	14,539,413
Baitfish/sportfish	22,491,297	22,491,297	–	–
Redfish	16,075,439	14,699,008	–	1,376,430
Atlantic Coast shellfish	9,361,237	–	9,361,237	–
TOTAL	621,121,875	200,631,196	329,876,697	90,613,982
Adjusted for coverage	806,651,785			

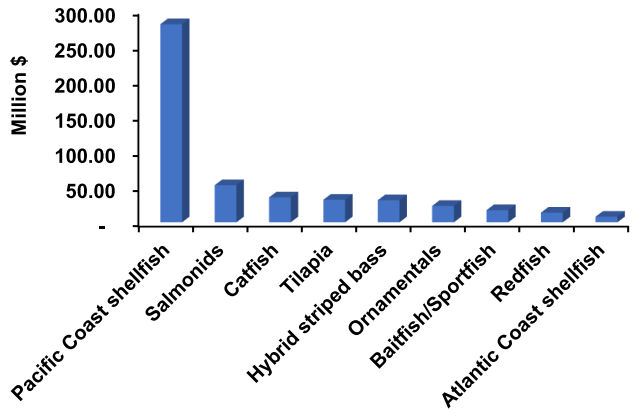

FIGURE 7 Lost revenue as a result of regulations by major sector of US aquaculture.

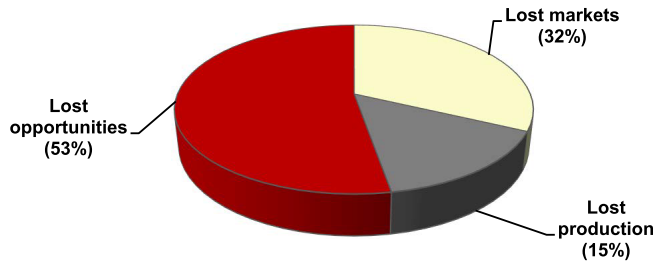

FIGURE 8 Lost revenue by category of loss. Values in percent of total lost revenue.

The greatest negative effects from regulations were on the smallest farm sizes, reflecting the high proportion of regulatory costs that are fixed and not variable costs (Table 2). Fixed costs as a percentage of total production and marketing costs ranged from 63% to 87% of regulatory costs across the various sectors. The regulatory compliance burden, therefore, largely affects US aquaculture businesses through increases in fixed costs that create additional

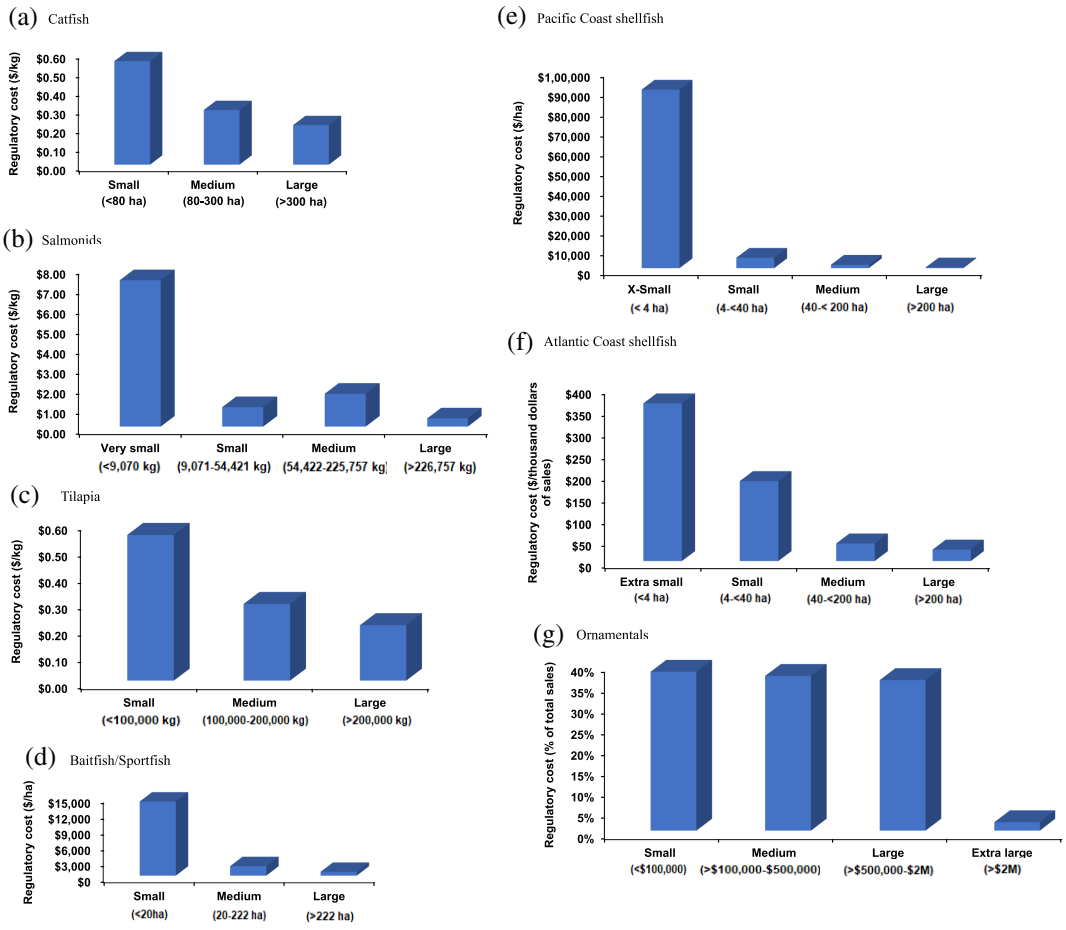

FIGURE 9 Effects of regulatory costs on farm size by major sector:(a) catfish ($/kg); (b) salmonids ($/kg); (c) tilapia ($/kg); (d) baitfish/sportfish ($/ha); (e) Pacific Coast shellfish ($/ha); (f) Atlantic Coast shellfish ($/thousand dollars of sales); and (g) ornamentals (% of total sales).

cost inefficiencies for all farms, but are especially onerous for small businesses. Greater fixed costs also increase costs on larger-scale farms, but the greater production volumes across which fixed costs are spread result in lower cost increases than on smaller-scale farms. The resulting per-unit production costs from greater fixed costs reduce competitiveness, increase the likelihood of business failure, and increase the number of farms that exit the industry. The disproportionately greater effect of regulations on small-scale farms likely explains the on-going trend of increasing farm size in aquaculture (USDA-NASS, 2019).

Regulatory costs on redfish farms also demonstrated a trend of decreasing costs with larger farm sizes, but data were not shown because of low numbers of farms (Engle & van Senten, 2023). There was no clear effect of farm size on hybrid striped bass farms, likely because of the low number of observations combined with a high percentage of responses from a state that restricted production to a low level.

4 | DISCUSSION

Rules and regulations are promulgated by governments in efforts to meet the desires of its citizens for a healthy environment, and safe food, highways, and places of work. US citizens enjoy a quality of life that has resulted from

the implementation and enforcement of regulations developed to achieve such quality (OMB, 2017, 2024). Regulations come at a cost to society and are worthwhile as long as the benefits exceed those costs. However, the evidence that the costs of US regulations have exceeded benefits has increased (Beales et al., 2017). Factors reported in the broader research literature on regulatory effects that contribute to excessive costs include inadequate attention to the best available science, lack of independent scientific review, and the continuous accumulation of regulations, particularly given the absence of sunset clauses, among others (Coffey et al., 2020).

US aquaculture producers have long reported regulations as a serious constraint (Gibson, 1979). This study offers the first estimate of the total national regulatory compliance burden on US aquaculture farms and confirms that regulatory costs have had substantial negative effects.

Environmental regulations generated the greatest regulatory costs. US citizens enjoy improved air and water quality as a result of regulatory actions, but the lack of parity in regulatory stringency between the United States and developing countries that export large quantities of farmed seafood to the United States (Abate et al., 2016; McDorman & Ström, 2006) can produce perverse results. By not holding imported seafood to the same regulatory rigor, the United States could be viewed as encouraging pollution of the environment from unregulated farms in other countries (Engle, 2019; Froehlich et al., 2020; Helvey et al., 2017). Decreased competitiveness of US aquaculture producers from the lack of equivalency in regulatory rigor was evidenced in catfish, tilapia, hybrid striped bass, and redfish sectors (Engle et al., 2023; Engle & van Senten, 2024; Hegde et al., 2023; Sun et al., 2023). The effect on competitiveness of US aquaculture is of concern given that the United States is one of the largest seafood markets in the world with the majority of its seafood supply imported with products that are less expensive because they are raised under less rigorous regulatory constraints. The resulting US seafood trade deficit was $20.3 billion in 2023 (Davis, 2024). Moreover, such an unintended consequence of the regulatory burden on US aquaculture businesses could potentially increase total global pollution. The decreased competitiveness results from greater production costs in the United States as compared with imported products that are not held to the same environmental management rigor as in the United States. The lower production costs from lack of adequate environmental controls allow imported products to be offered at a lower price, thereby increasing the quantity demanded and sold in the United States. Such increased demand for products without adequate environmental controls potentially increases the overall volume of global pollution above what it would be if greater US consumption was from US farms operated under its stringent regulatory and enforcement systems. More efficient approaches are needed that provide adequate oversight over environmental management but that do not threaten the economic sustainability of US aquaculture (Cochrane, 2022; Mandel & Carew, 2013; Noe, 2016). One such approach is delineated in recommendations made in the European Union (EU) to require countries that export seafood to the EU to meet all EU food safety and environmental regulations (European Commission, 2022). A similar approach could be considered in the United States for imported seafood.

Eighty-five percent of US aquaculture farms are small businesses (USDA-NASS, 2019). Despite guidance from the Office of Management and Budget to consider distributive impacts in rule-making processes (Executive Order 14094, 2023), smaller-scale aquaculture farms experience much greater regulatory costs than larger farms. Of equal concern is that regulations prevented small-scale shellfish producers from adopting new technologies with less environmental impact (van Senten et al., 2020). Moreover, total regulatory effects tended to be greater in areas with large farm clusters, such as catfish (Hegde et al., 2022), crawfish (McClain et al., 2005), tilapia (Engle et al., 2023), and ornamental fish (Boldt et al., 2023) because of the greater numbers of farms and total production affected in those areas.

Findings that regulatory costs were primarily fixed costs in aquaculture, as on California agriculture farms (Hurley & Noel, 2006), may partially explain reports that regulatory compliance requirements have decreased farm-level efficiencies in Norway (Asche & Roll, 2013). In the United States, a 10% reduction in manpower cost spent on regulatory compliance was found to increase technical efficiency by 77.5% on US baitfish/sportfish farms (van Senten et al., 2018a).

Regulatory costs were found to have become one of the top five costs of production on US aquaculture farms. Increased costs have economic consequences. Businesses that sell products with inelastic demand and few close substitutes, such as oysters and live fish sold to live fish markets, may be able to pass increased costs on to customers. Other sectors, however, such as catfish and trout that face more elastic demand in foodfish markets, in which consumers readily substitute other species, cannot pass such increased costs on to consumers. The result for those sectors is reduced price competitiveness as compared with international suppliers who are not required to internalize environmental regulatory costs. There also are economic consequences for sectors selling products with inelastic demand and few substitutes. Those businesses may be able to continue selling products, but may lose low-income consumers who are unable to pay the higher costs. Market intermediaries may similarly be affected by the increased costs that may force businesses to reduce employment or make other adjustments as necessary. Increasing prices of goods tend to result in lower quantities purchased overall. Given priorities of increasing seafood consumption for health and food security in the United States, higher prices of seafood will have the opposite effect of reducing the quantity demanded.

Listing farmed species in trade as injurious under the Lacey Act has negatively affected US farms by reducing risk management strategies of production diversification and restricting access to markets. For catfish, effects included: (1) reduced product diversification and economies of scope from listing bighead carp (Hegde et al., 2023); (2) loss of the best control method for the *Bolbophorus* spp. parasite (Ledford & Kelly, 2006; Thomas & Hanson, 2007) from listing black carp; and (3) closure of black and bighead carp hatcheries (Hegde et al., 2023). Bighead carp sales provided additional revenue to catfish farms that have not been recovered because there is no other commercially viable filter-feeding fish that can be raised efficiently in polyculture with catfish. The use of black carp to minimize losses to a trematode parasite was the only effective treatment for the trematode (Wui & Engle, 2007), and losses to the trematode have continued on catfish farms. While the US Court of Appeals ruled in 2017 that the Lacey Act could not be used to regulate interstate movement of injurious species, the losses on catfish farms have continued because of the absence of supplies of bighead and black carp fingerlings (Hegde et al., 2023). On-going attempts to reinstate the authority of the United States Fish & Wildlife Service to regulate interstate movement of injurious species listings to various pieces of federal legislation that continued in 2021–2022 (See Engle et al., 2024a for specifics) create potential risks to hatcheries that once supplied bighead and black carp fingerlings. On-going proposals to add blue catfish, tilapia, red swamp crawfish, grass carp, koi, guppy, and goldfish, all aquaculture species in trade in the United States, to the List of Injurious Species were found to potentially result in losses of $452 million in total economic output, nearly 5000 jobs, and $35 million in tax revenue (Engle et al., 2024a).

Severe actions by enforcement officers such as heavy fines, threats of felony charges, or mandatory jail time have a chilling, deterrent effect on aquaculture. For example, a paperwork violation under the Lacey Act resulted in felony charges with threatened fines of up to $500,000 and 5 years in jail (Rumley, 2010). Engle et al. (2019) reported that onerous regulations in a state that had been a major trout-producing state resulted in the exodus of more than 25 trout farms in that one state.

One of the limitations of this study was the nature of the underlying survey data. The data from each survey reflects a snapshot of events in the specific year of data collection. A regulatory action that resulted in substantial effects the year following the survey would not have been captured. Moreover, the surveys were conducted in different years, with some of the data handled differently in earlier than in later years. This analysis re-visited the raw data to aggregate responses in a consistent manner and adjusted USD values to constant 2023 equivalents. As a result, specific values in this analysis differ from those in the original publications. Finally, the response and coverage rates in the Atlantic Coast shellfish survey were noticeably lower than those in the other surveys. Regulations were likely of less importance to Atlantic Coast shellfish producers, but it is also possible that there were other reasons for the low response rates that were unknown to the authors.

4.1 | Pathways towards more efficient regulations

Are there pathways toward more cost-efficient approaches to regulation of aquaculture in the United States that still provide adequate oversight? The literature on the effects of regulations has identified key elements required for more efficient approaches to regulations that further suggest pathways for more efficient, lower-cost regulation of US aquaculture.

4.1.1 | Key elements of more efficient regulatory approaches

Regulations are developed with the intention to enhance the wellbeing of society (Beales et al., 2017). A growing body of research, however, has raised concern over the inefficiencies created by the rate of increase of regulations that compound negative effects on businesses (Mandel & Carew, 2013) through unreasonable compliance costs (OMB, 2017), reduced economic growth (Dawson & Seater, 2013), decreased productivity (McGrattan & Prescott, 2012), reduced adoption of technological innovations (Oster & Quiglay, 1977; Porter & van der Linde, 1995), and increased income inequality (Chambers et al., 2018). Economic growth was reduced by 0.8% per year from 1980 to 2012 and by 2% per year from 1949 to 2005 because of regulations according to Coffey et al. (2020) and Dawson and Seater (2013), respectively. The growing literature on negative effects of the growing regulatory framework in the United States has led to calls for "smarter" (Cochrane, 2022; Mandel & Carew, 2013; Noe, 2016), more cost-effective, approaches to regulation (Beales et al., 2017; Hahn, 1996). The following summarizes key elements of more efficient approaches to regulation from research literature.

Beales et al. (2017) argued that regulators should follow a "First do no harm" approach. Benefit–cost analysis is the tool required for federal rules (Executive Order 12866, 1993) to determine whether private markets, the required trigger for rule-making, have failed (Executive Order 12866, 1993). Few rules, however, adequately assess whether private markets have failed. The common use of benefit–cost analysis appears to have had little effect on the accumulation of unreasonable regulatory compliance costs (National Center for Environmental Economics, 2014). Industries that are not well understood and are changing rapidly, such as aquaculture, are at greater risk of substantial harm from regulatory action, particularly if insufficient effort is made to identify and estimate potential unintended consequences (Beales et al., 2017; Osmundsen et al., 2017). Avoiding greater harm than good through well-designed regulations requires that the rules developed be tailored to the issue at hand, and the potential costs to the regulated sector studied and analyzed in detail.

Well-designed regulations should: (1) avoid precautionary approaches and focus on the best available scientific information; (2) adopt collaborative and participatory approaches throughout; (3) include sunset clauses that require periodic review to determine whether the need still exists followed by removal of outdated regulations; and (4) allow for flexibility by favoring market-based over command-and-control approaches (Beales et al., 2017).

Precautionary approaches to regulation that are not based on detailed analysis and understanding of the best available scientific information can lead to mistakes with serious consequences for the economic sectors affected (Beales et al., 2017; Foster et al., 2000). Regulatory agency staff rarely have in-depth expertise across the many subject matter areas relevant to any particular issue and are unlikely to have time to fully digest the relevant scientific knowledge. Engaging teams of independent experts to provide comprehensive technical reviews would reduce the chances of missing critical data or a final determination that potentially reflects biases of individual agency staff (Abate et al., 2018; Beales et al., 2017).

Collaborative, participatory approaches (as specified in Executive Order 14094, 2023 and earlier by Executive Order 12866, 1993) of active engagement among farmers, regulators, and independent experts lead to practical rules that are more effective at meeting societal goals (Carr, 2015; Osmundsen et al., 2017; Palmer et al., 2013; Rubino & Wilson, 1993; Stead, 2005). As an example, the US Environmental Protection Agency (USEPA) chose a participatory approach to develop the 2004 rule on effluents from aquaculture (USEPA, 2004). The rule-making effort was

triggered by pressure from environmental Non-Governmental Organizations and a subsequent court decree to add additional industries, including aquaculture, to the National Pollutant Discharge Elimination System permitting process (Tucker & Hargreaves, 2008). The Aquaculture Effluents Task Force (AETF) formed in 1999 consisted of approximately 200 individuals including scientists from various disciplines, producers, Extension personnel, and NGOs organized into 11 technical subgroups. What began as a contentious matter resulted in a final rule widely viewed to be reasonable because the agency made final decisions based on the data, analyses, and suggestions provided by AETF participants (Engle et al., 2005; Tucker & Hargreaves, 2008).

The lack of a specified timeline for evaluation of the continuing need for a specific regulation (Dudley, 2014) has led to a substantial accumulation of regulations (Noe, 2016) with the size of the Federal Register alone increasing by 12% from 2022 to 2023 to 90,402 pages. The cumulative increase in pages in the Federal Register from 1976 to 2023 was 58% (Crews, 2023). Without removal of outdated rules, such continuous accumulation has contributed to redundancy and inefficiency (Beales et al., 2017). Retrospective review of all rules is needed to seek ways to eliminate overlap, and to streamline and simplify rules and compliance requirements (Asche & Smith, 2018; Hishamunda et al., 2012).

Flexible approaches that create incentives for business innovation are likelier to result in more efficient regulatory approaches than a single generalized approach (Ambec et al., 2011; Porter & van der Linde, 1995). Inflexible rules were found to quickly become obsolete from the rapid pace of technological development in aquaculture (Osmundsen et al., 2017). The diversity and variability of aquaculture farms by geographic region, size, scope, and business model (Engle et al., 2020; Johnson et al., 2014; Kumar et al., 2020) requires a more flexible, market-based approach than the more common command-and-control approaches that often produce unintended consequences (Engle & Wossink, 2008; Hishamunda et al., 2012).

4.1.2 | Specific pathways with potential to improve the efficiency of US regulations with respect to aquaculture

The evidence of the negative effect of the US regulatory framework on the competitiveness of US aquaculture has grown substantially (Engle & Valderrama, 2002; Engle & Stone, 2013; Abate et al., 2016; Engle et al., 2019; Engle & van Senten, 2022, 2023) and has decreased the overall economic contributions from aquaculture (Kumar et al., 2024). This body of work has pointed to a clear need for reform and efforts to develop "smarter," more efficient regulations. Table 4 lists specific pathways suggested by research on farm-level effects on aquaculture farms that could lead to reduced regulatory costs, improved competitiveness, and growth of US aquaculture.

Renewed recognition of the potential benefits to the United States of expansion of commercial aquaculture is evidenced by the Executive Order requiring federal coordination of aquaculture (Executive Order 13921, 2020), "Promoting American Seafood Competitiveness and Economic Growth", issued in 2020. This Executive Order called for a series of national plans for aquaculture that were subsequently developed by the US federal interagency Subcommittee on Aquaculture. The 2022 National Strategic Plans for Aquaculture Research and to Enhance Regulatory Efficiency in Aquaculture, and the 2024 National Strategic Plan for Aquaculture Economic Development were designed to support growth of US aquaculture (USDA-ARS, 2024). Additional work has continued on the development of a national aquatic animal health plan along with the development of a variety of tools intended for use by those seeking to navigate the permitting process for marine aquaculture farms (NOAA, 2024).

Rule-making process pathways to improve the efficiency of regulations

Each rule developed should include a sunset clause that specifies a date that triggers an evaluation of whether objectives have been met, whether the rule has become outdated and whether it is time to remove or amend the rule. Rule development should include specific guidelines for reward incentives for those producers who can demonstrate a record of compliance. An example of a strong incentive would be specified reductions in the frequency of testing

TABLE 4 Pathways identified for improving the efficiency and reducing compliance costs of regulations.

Recommended pathways	Regulatory category
Rule-making	
• Add sunset clauses that specify a date that triggers evaluation of whether objectives were met, whether the rule is outdated and should be removed.	All rules
• Build incentives for producers with good records of compliance that would include reduction in the frequency of testing and other cost-reduction actions.	Fish health and effluent testing
• Reduce fish health testing costs by restricting testing to the most susceptible species and life stages, developing nonlethal inspection methods for health status determination.	State permits to import fish that require proof of health status
• Compensate aquaculture producers for losses from the reverse externalities of avian predation.	USFWS, USDA
• Develop appropriate risk management approaches that carefully evaluate costs, and benefits rather than highly prescriptive or precautionary approaches.	Aquatic nuisance species, actions involving fish health
Implementation	
• Training programs for regulatory personnel.	All rules
• Develop clear, transparent appeals procedures communicated to producers by inspectors.	All rules
• Reduce delays in permitting.	All rules
• Develop educational programs for state agriculture, natural resources, fisheries & wildlife agencies, environmental agencies on current state of science and knowledge with respect to aquaculture generally but also on pathogens, disease risk, and risk management.	All rules
• Develop a mechanism to form teams of experts available to assist states to make timely, appropriate, and economical decisions related to interventions on aquaculture farms, whether for fish health, invasive species, or other concerns.	All rules
Research needed	
• Develop nonlethal inspection methods to avoid killing healthy fish to prove health status.	Fish health testing
• Development and approval of multipathogen testing methods	Fish health testing

for fish health status or effluents that would reduce time and associated costs for those farms with a record of compliance over time.

Fish health testing rules should be standardized across states to specify the sample size and require farm- rather than lot-level testing. Testing should be required only for species and size and age classes that are most susceptible to the pathogens of concern. Methods of non-lethal fish health status testing are needed to avoid sacrificing healthy fish, as well as development and approval of multi-pathogen testing methods to further reduce fish health testing costs.

Programs are needed to compensate private fish farmers for suffering related to losses from the reverse externalities of federally protected avian predators. Compensation should include the costs of managing bird predation to attempt to reduce losses using non-lethal methods and the value of the losses themselves.

Appropriate risk management strategies are needed for rules related to aquatic invasive species and responses to disease outbreaks. Risk management approaches, when applied appropriately, have mitigated negative impacts on the environment, economy, and human health (Hill et al., 2018; Hill & Zajicek, 2007). Risk-based approaches similar

to those used in other livestock sectors that carefully evaluate costs and benefits (Häsler et al., 2011; Oidtmann et al., 2011), if developed appropriately, have potential to substantially reduce fish health testing costs (van Senten et al., 2018b; Engle et al., 2021). Surveillance of aquatic pathogens in the wild is critical to understanding risks associated with aquatic animal health diseases and choosing effective intervention methods. Risk management approaches, however, require detailed analysis, training, and specific skills rarely available in many regulatory agencies. Without the required expertise, regulatory agencies tend to default to overly risk-adverse, precautionary approaches that may not reflect realistic assessments of the level of risk to the environment. Mechanisms to provide the necessary scientific expertise are needed through cooperation across regulatory agencies, aquaculture associations, and research institutions.

Pathways related to implementation of rules for aquaculture

Training programs are needed for regulatory personnel at the state and federal levels on the current state of scientific knowledge of aquaculture generally but also on specific current issues of concern. Survey respondents generally reported a high amount of turnover among state agency personnel tasked with implementing rules for aquaculture. Turnover was reported as a factor leading to inconsistent and inappropriate (i.e., erroneous) instructions received from inspectors, in some instances from within the same agency. The inexperience of inspectors combined with little to no background or training in aquaculture in these instances led to high compliance costs on farms that included unreimbursed legal expenses for successful appeals (Engle et al., 2019; Osmundsen et al., 2017).

Training programs could be organized by the federal interagency Subcommittee on Aquaculture by assembling teams of experts in key regulatory areas, such as fish health, water quality, aquatic invasive species, and risk analysis. Training programs for regulatory personnel would be enhanced by the development of published summaries of the relevant scientific base of knowledge by research and Extension personnel. Provisions could also be made for the teams of experts formed to assist with deliberations of regulatory agency personnel to better understand the risks associated with issues of concern and to chart more effective pathways for managing those issues.

There is a strong need for clear and transparent appeals to be specified for each rule by each regulatory agency. Survey respondents reported challenges in identifying the appropriate agency personnel for questions and follow-up to inspector reports. Details on filing an appeal, including the name and contact information of the supervisor should be included in any written correspondence received by the producer from a regulatory agency.

The frequency of extended delays in permitting must be reduced. Each rule should establish and adhere to deadlines by which relevant agencies make their determination and notify the producer (Abate et al., 2018). Second, rule-making processes that involve more than one agency or entity, should be conducted concurrently, not sequentially. The need to reduce delays includes the need to improve and expedite the approval mechanisms for drugs and chemicals for non-food aquaculture products.

The need for reliance on the best available science to develop effective regulations combined with the general scarcity of agency staff knowledgeable about aquaculture is problematic. The inter-agency Subcommittee on Aquaculture could form a series of teams of experts in various relevant disciplines (i.e., production practices, aquatic animal health, water quality, aquatic invasive species, and economics) who are willing to engage with regulatory agencies in pragmatic rule-making, in responding to disease outbreaks or other events, and otherwise work to ensure that deliberations are based on the best available science. The availability of expert advice during rule-making should include in-depth consideration of potential unintended consequences.

4.2 | Other factors that contribute to the total regulatory burden and reduced growth of US aquaculture and potential pathways for improvement

The total estimated regulatory burden on US aquaculture was based on data and responses from existing aquaculture farm businesses, and does not include estimates of the size, scope, and scale of what US aquaculture could be if

still other factors had not constrained its growth and development. This section discusses other factors that are related to actions taken by regulatory agencies that may have contributed to the slower rate of growth of US aquaculture as compared with other countries, particularly with regard to marine finfish aquaculture. These other factors can also increase delays in permitting, increase costs, prevent growth, and development of new US aquaculture sectors, and result in additional unintended consequences. The following section will discuss some additional factors: (1) general lack of understanding and knowledge of aquaculture on the part of state and federal agency personnel (Osmundsen et al., 2017) and of the general public; (2) conflicts among user groups and special interest groups, including "Not-In-My-Backyard" (NIMBY) effects (Alvarez, 2021); (3) the US legal system that provides incentives for legal challenges to proposed investments in aquaculture (USEPA, 2024); (4) inconsistent enforcement of regulations between publicly funded aquaculture (especially state and federal hatcheries) and private commercial aquaculture farms, (5) unwillingness on the part of agencies to seek out or take advantage of scientific experts when deliberating on a course of action; and (6) an inadequate regulatory framework for aquaculture in public waters, especially marine environments (Rubino, 2022).

4.2.1 | Lack of understanding and knowledge of aquaculture

Aquaculture in the US, despite shellfish farms dating back to the late 1800s (Engle & van Senten, 2024), has been a relatively unknown and unrecognized sector of agriculture among the general public and among agency personnel charged with the development and enforcement of regulations. Many myths circulate among the general public (See Zajicek et al., 2021 for examples related to marine aquaculture) that are contrary to scientific data. The widespread misunderstandings of aquaculture are similarly found among agency personnel who have no training or background in aquaculture (Osmundsen et al., 2017). Agencies charged with protecting environmental resources more frequently are trained in environmental science, ecology, or natural resources and are often reported to be averse to allowing even sustainable human uses of natural resources (Abate et al., 2018).

Pathways for alleviating the widespread lack of knowledge related to science-based facts of US aquaculture can only be addressed through similarly widespread efforts to increase aquaculture literacy among the general public and more specifically with public (local, state, and federal) agencies that play a regulatory role in aquaculture. Aquaculture literacy programs need to include publishing the latest science-based information in the form of fact sheets, posting videos on YouTube, Instagram, and other widely viewed platforms, through engagement at regional and national conferences attended by natural resource agency officials, and stories posted across many readily available and accessed platforms. Increasing aquaculture literacy is a long-term effort that will require active support and engagement by the major agencies that fund aquaculture work, including the United States Department of Agriculture and the National Oceanic and Atmospheric Administration (Office of Aquaculture and Sea Grant).

4.2.2 | Conflicts among user groups and special interest groups, including "not-in-my-backyard" (NIMBY) opposition to aquaculture

Expansion of aquaculture in public waters of the United States has been thwarted by active opposition from special interest groups. Some of the opposition is from local user groups such as landowners, commercial fishermen, and those who enjoy recreation in public water areas proposed for aquaculture development. Some opposition stems from Not-In-My-Backyard (NIMBY) perspectives of those who purchased expensive homes with a pristine view of a public water body, and who oppose the location of aquaculture farms with buoys, cages, or other structures within viewing distance of their homes. In other cases, opposition to specific proposed aquaculture farms has come not from local residents but environmental activists from around the country who convene to openly oppose specific proposed aquaculture farms (Alvarez, 2021). Widely publicized examples include opposition to a pilot net-pen farm

in the Gulf of Mexico (Guthrie et al., 2024), and the 2018 ban on salmon net-pen farming in Puget Sound, Washington (Engle & van Senten, 2024), among others.

Pathways and sustained action are needed to alleviate the escalation of conflicts among user groups that have resulted in prohibitions of sustainable aquaculture development. An important, although long-term pathway is the development and implementation of a long-term aquaculture literacy campaign that addresses the core issues raised by those who oppose aquaculture development through summary reviews of the relevant scientific literature. On the local level, a potential pathway is that of community-based engagement to develop and sustain a trust-based social license to operate. Third-party honest brokers, such as land-grant Extension and NOAA-Sea Grant personnel, university scientists, and aquaculture industry associations can be effective in facilitating community-based engagement to seek common ground and work through potential conflicts before issues escalate.

4.2.3 | Legal system that allows/encourages lawsuits

The US legal system provides mechanisms for citizens to file lawsuits under the Clean Water Act (Title 33 Navigation and Navigable Waters, Chapter 26 Water Pollution Prevention and Control §1365. Citizen suits) and further provides reimbursement of legal fees if the plaintiff is successful (USEPA, 2024). Such lawsuits from opponents of aquaculture development projects have the potential to force reduction of the scale of the business to one that is not feasible and can add unnecessary and costly monitoring and reporting requirements. The possibility of such lawsuits creates an incentive for regulatory agencies to be more conservative in decision-making and to rely on precautionary, rather than science-based evaluation of the likely risks.

Pathways for improvement would include examination of the use of the Citizen suits provision of the Clean Water Act to determine whether this provision has fulfilled its original intent and purpose. Lawsuits filed under this provision have resulted in extensive and lengthy delays in permit approvals restricting growth and expansion of US aquaculture. This provision of the Clean Water Act is often used as a mechanism primarily to obstruct aquaculture development and not one that is adhering to the goals and intent of the Clean Water Act.

4.2.4 | Not all rules and regulations are enforced equally on publicly funded aquaculture facilities as compared with private, commercial aquaculture producers

State and federal hatcheries in the United States have long histories of farming many species of coldwater and warmwater finfish and shellfish species for stocking into natural water bodies. While many stockings support recreational fishing opportunities across the continental United States, those in Alaska support the commercial salmon fishery. Other publicly funded hatchery production is used for conservation goals related to threatened and endangered species. State agencies with authority over stocking activities in waters of the state have been reported to have enacted more stringent fish health inspection and other requirements for commercial private farms than what is practiced on state-funded hatcheries under the jurisdiction of the same agency (Engle et al., 2019).

4.2.5 | Agency decisions are not based on the best available science

Most federal agencies in the United States are required to base decisions on the best available science, but few state agencies are similarly required to seek out and utilize the relevant science related to rule-making processes. State agency budgets frequently do not allow for hiring experts in the various industries and disciplines required. However, US aquaculture producers further report that agency personnel are unwilling to take advantage of the knowledge of recognized experts in relevant disciplines even when their service is offered at no cost to the agency.

The combined effects of the lack of internal expertise and the apparent unwillingness to seek out expert advice results in lengthy permit processing and a tendency for agencies to be unwilling to approve permits for projects that have become controversial through public opposition.

A pathway towards improvement of this constraint to aquaculture development is for a federal agency engaged with aquaculture, such as NOAA, USDA, or the Subcommittee on Aquaculture, to assemble teams of experts in disciplines relevant to the most common regulatory actions to respond to the need for access to the best available science. Experts who agree in advance to serve on one or more response teams could potentially be available to assist state and federal agencies by providing the best available science. The Aquaculture Effluents Task Force (AETF) formed in 1999 by USEPA and USDA (Engle et al., 2005; Tucker & Hargreaves, 2008) is an example of a successful initiative that could be implemented for on-going support.

4.2.6 | Inadequate regulatory framework for aquaculture in marine environments

The United States lags behind many other countries in the development of marine aquaculture (Engle, Boldt, et al., 2024; Rexroad et al., 2021; Rubino, 2022). There are various factors that contribute to the lag in commercial marine finfish in the US, but the foundational issue is that the current US regulatory framework is not adequate for marine aquaculture. Marine waters are public resources with complex sets of jurisdictions. There is no clear pathway for permitting aquaculture development in federal waters. Attempts to apply commercial fishing laws, such as the Magnusson-Stevens Act, to aquaculture have been shown to be inappropriate. Other commercial fisheries laws applied to aquaculture have led to prohibition of farming species such as striped bass that are harvested commercially from federal waters. Citizen lawsuits allowable under the Clean Water Act have delayed permitting and discouraged investment in marine aquaculture businesses. Other federal laws such as the Endangered Species Act, the Marine Mammal Protection Act (i.e., the essential fish habitat review), apply to marine waters and often require additional expensive and lengthy studies and reviews such as those required by the US Army Corps of Engineers for permits. Underpinning most environmental regulations is the National Environmental Policy Act that requires Environmental Impact Statements (EIS) for new projects that can cost $1 to $2 million. New projects in marine waters also require a series of additional studies to be conducted by engineering, environmental, and other consultants that cost millions of dollars for the initial permitting process alone. Such upfront costs and delays reduce the attractiveness of investments in the United States and often lead to multinational and other investors to develop projects in less regulated countries, to the detriment of US mariculture development.

The key pathway needed is for a concerted effort to develop an efficient, streamlined, and coordinated permitting and regulatory framework for marine aquaculture in the United States. The effort will require collaboration among the regulatory entities with jurisdiction over marine environments, including the Department of Commerce, the Department of the Interior, the US Fish & Wildlife Service, the US Army Corps of Engineers, and others. The effort will need to include measures and engagement that avoids the pitfalls of lawsuits and other legal action designed primarily to delay project initiation.

5 | CONCLUSIONS

Regulations have long been mentioned as a major problem by US aquaculture producers. This study is the first to estimate the national economic effects of the total suite of regulations with which US aquaculture producers must comply. The total national cost of compliance with regulations was $196 million annually and constituted one of the top five costs of production across all major sectors of US aquaculture. Regulatory costs were found to represent from 9% to 30% of total farm costs, with high percentages of regulatory costs fixed, rather than variable costs. Increased economies of scale pose serious challenges for small-scale farms and threaten their economic

sustainability. Environmental regulations generally resulted in the greatest costs overall, but there was substantial variability as to which specific regulations imposed the greatest costs across aquaculture sectors. The negative effects of regulations included lost revenue in addition to increased costs. Lost revenue resulted from markets and production lost as a result of regulatory action, and lost opportunities of farms seeking to expand but prevented from doing so by regulatory action. Total annual lost revenue summed to $807 million per year and indicated that US aquaculture, if not constrained by regulatory action, could have been 36% greater than it was at the time of this study. The total foregone economic contribution from lost revenue was estimated to be $1.4 billion along with more than 8000 jobs foregone from farm effects alone, not including effects from supply chain partners.

This research on the US regulatory framework suggests that smarter, more cost-effective regulations that provide the same or greater oversight should: (1) avoid precautionary approaches and focus on the best available scientific information; (2) adopt collaborative and participatory approaches throughout; (3) include sunset clauses that require periodic review of continued need with removal of outdated regulations; and (4) favor flexible, market-based rather than command-and-control approaches. This analysis concluded with suggestions for pathways for improving regulatory efficiency and reducing compliance costs from regulatory actions.

ACKNOWLEDGMENTS

Funding was provided by the USDA-Economics Research Service through Cooperative Agreement Number 58-6000-2-0122 to Virginia Tech University. The project team thanks all the US aquaculture producers who participated in the surveys that provided the underlying data for this project. The authors are solely responsible for any errors or omissions.

DATA AVAILABILITY STATEMENT

The availability of data is restricted due to privacy/ethical restrictions.

ORCID

Carole R. Engle https://orcid.org/0000-0003-4085-9429
Jonathan van Senten https://orcid.org/0000-0002-3513-7600
Ganesh Kumar https://orcid.org/0000-0003-4765-5306
Matthew A. DiMaggio https://orcid.org/0000-0001-9148-9785

REFERENCES

Abate, T., Nielsen, R., & Nielsen, M. (2018). Agency rivalry in a shared regulatory space and its impact on social welfare: The case of aquaculture regulation. *Aquaculture Economics & Management*, *22*(1), 27–48.

Abate, T. G., Nielsen, R., & Tveteras, R. (2016). Stringency of environmental regulation and aquaculture growth: A cross-country analysis. *Aquaculture Economics & Management*, *20*(2), 201–221. https://doi.org/10.1080/13657305.2016.1156191

Alvarez, N. D. (2021). *NIMBY: A look into public perceptions of aquaculture*. Master's Thesis (3492). Electronic Theses and Dissertations. https://digitalcommons.library.umaine.edu/etd/3492

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2011). *The Porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness?* Discussion Paper 11–01. Resources for the Future.

Antle, J. M. (2000). No such thing as a free safe lunch: The cost of food safety regulation in the meat industry. *American Journal of Agricultural Economics*, *82*(2), 310–322.

Asche, F., & Roll, K. (2013). Determinants of inefficiency in Norwegian salmon aquaculture. *Aquaculture Economics & Management*, *17*(3), 300–321.

Asche, F., & Smith, M. D. (2018). Viewpoint: Induced innovation in fisheries and aquaculture. *Food Policy*, *76*, 1–7.

Bailey, J., & Thomas, D. W. (2017). Regulating away competition: The effect of regulation on entrepreneurship and employment. *Journal of Regulatory Economics*, *52*(3), 237–254.

Beales, H., Brito, J., Kennerly, J. D., DeMuth, C., Devine, D., Dudley, S., Mannix, B., & McGinnis, J. O. (2017). *Government regulation: The good, the bad, & the ugly*. Regulatory Transparency Project, The Federalist Society.

Boldt, N. C., Engle, C. R., van Senten, J., Cassiano, E. J., & DiMaggio, M. A. (2023). A regulatory cost assessment of ornamental aquaculture farms in Florida. *Journal of the World Aquaculture Society*, *54*(3), 714–733. https://doi.org/10.1111/jwas.12881

Botta, R., Court, C. D., Ropicki, A., & Camp, E. V. (2021). Evaluating the regional economic contributions of US aquaculture: Case study of Florida's shellfish aquaculture industry. *Aquaculture Economics & Management*, *25*(2), 223–244. https://doi.org/10.1080/13657305.2020.1869860

Carr, G. (2015). Stakeholder and public participation in river basin management-an introduction. *WIREs Water*, *2*(4), 393–405.

Chambers, D., McLaughlin, P. A., & Stanley, L. (2018). Barriers to prosperity: The harmful impact of entry regulations on income inequality. *Public Choice*, *180*, 165–190.

Chang, T., Zivin, J. G., Gross, T., & Neidell, M. (2016). Particulate pollution and the productivity of pear packers. *American Economic Journal: Economic Policy*, *8*(3), 141–169.

Cochrane, J. (2022). Time for supply. *The Grumpy* Economist. https://johnhcochrane.blogs, pot.com/2022/03/time-for-supply.html Accessed 2 April 2022.

Coffey, B., McLaughlin, P. A., & Peretto, P. (2020). The cumulative cost of regulations. *Review of Economic Dynamics*, *38*, 1–21.

Crain, N. V., & Crain, W. M. (2023). *The cost of federal regulation to the US economy, manufacturing and small business*. National Association of Manufacturers.

Crews, C. W. (2023). Biden's 2023 Federal Register page count is the second-highest ever. Forbes Magazine. Available at: https://www.forbes.com/sites/waynecrews/2023/12/29/bidens-2023-federal-register-page-count-is-the-second-highest-ever/?sh=5244115e1432 Accessed May 22, 2024.

Currie, J., & Walker, R. (2019). What do economists have to say about the clean air act 50 years after the establishment of the Environmental Protection Agency? *Journal of Economic Perspectives*, *33*(4), 3–26.

Curtis, E. (2018). Who loses under cap-and-trade programs? The labor market effects of the NOX budget trading program. *Review of Economics and Statistics*, *100*(1), 151–166.

Davis, C. (2024). *US seafood imports exceeded exports by $20.3 billion in 2023*. Economic Research Service, US Department of Agriculture.

Dawson, J. W., & Seater, J. J. (2013). Federal regulation and aggregate economic growth. *Journal of Economic Growth*, *18*, 137–177.

Dicks, M. R. (1996). *Economy-wide impacts of US aquaculture*. Oklahoma Agricultural Experiment Station, Division of Agricultural Sciences and Natural Resources. Oklahoma State University.

Dudley, S. (2014). *The utility of humility*. The George Washington University.

Duff, J. A., Getchis, T. S., & Hoagland, P. (2003). *A review of legal and policy constraints to aquaculture in the US northeast*. Northeast Regional Aquaculture Center.

Engle, C., & van Senten, J. (2024). *Washington aquaculture*. Western Region Aquaculture Center Fact Sheet, University of Washington.

Engle, C. R. (2019). Bringing aquaculture sustainability down to earth. *Journal of the World Aquaculture Society*, *50*(2), 246–248.

Engle, C. R., Boldt, N., van Senten, J., & Schwarz, M. (2024). Estimating growout production costs of commercial-scale marine finfish production in southern tier US states. *Journal of the World Aquaculture Society*, *55*(4), e13075. https://doi.orgt/10.1111/jwas.13075

Engle, C. R., Kumar, G., & van Senten, J. (2020). Cost drivers and profitability of US pond, raceway, and RAS aquaculture. *Journal of the World Aquaculture Society*, *51*(4), 847–873. https://doi.org/10.1002/JWAS.12706

Engle, C. R., Pomerleau, S., Fornshell, G., Hinshaw, J. M., Sloan, D., & Thompson, S. (2005). The economic impact of proposed effluent treatment options for production of trout *Oncorhynchus mykiss* in flow-through systems. *Aquacultural Engineering*, *32*(2), 303–323.

Engle, C. R., & van Senten, J. (2023). US hybrid striped bass and redfish farms: Economic effects of the US regulatory framework. *North American Journal of Aquaculture*, *85*(4), 293–310. https://doi.org/10.1002/naaq.10297

Engle, C. R., & Stone, N. M. (2013). Competitiveness of US aquaculture within the current US regulatory framework. *Aquaculture Economics & Management*, *17*(3), 251–280. https://doi.org/10.1080/13657305.2013.812158

Engle, C. R., & Valderrama, D. (2002). The economics of environmental impacts of aquaculture in the United States. In J. R. Tomasso (Ed.), *Aquaculture and the environment in the United States* (pp. 247–270). U.S. Aquaculture Society.

Engle, C. R., & van Senten, J. (2022). Resilience of communities and sustainable aquaculture: Governance and regulatory effects. *Fishes*, *7*(5), 268. https://doi.org/10.3390/fishes7050268

Engle, C. R., van Senten, J., Clark, C., & Boldt, N. (2023). Has the regulatory compliance burden reduced competitiveness of the US tilapia industry? *Fishes*, *8*(2), 151. https://doi.org/10.3390/fishes8030151

Engle, C. R., van Senten, J., & Fornshell, G. (2019). Regulatory costs on US salmonid farms. *Journal of the World Aquaculture Society*, *50*(3), 522–549. https://doi.org/10.1111/jwas.12604

Engle, C. R., van Senten, J., Schwarz, M., Hartman, K., Gustafson, L., Johnson, K., & Creekmore, L. (2021). Farm-level cost drivers of salmonid fish health inspections. *Journal of Aquatic Animal Health*, *33*(4), 199–219. https://doi.org/10.1002/aah.10139

Engle, C. R., van Senten, J., Tuckett, Q., & Hill, J. (2024). Potential economic impact on US aquaculture of injurious species listing of major aquaculture species. *Journal of the World Aquaculture Species*, *55*(1), 89–109. https://doi.org./10.1111/jwas.13044

Engle, C. R., & Wossink, A. (2008). Economics of better management practices in aquaculture. In C. Tucker & J. Hargreaves (Eds.), *Environmental best management practices for United States aquaculture* (pp. 519–552). Blackwell Publishing.

European Commission. (2022). Application of EU health and environmental standards to imported agricultural and agri-food products. Report 226, Commission to the European Parliament and the Council, Brussels, The European Union.

Executive Order No. 12866. (1993). Regulatory planning and review. *Federal Register 58*, Section 1a, No. 190. Available at: https://www.archives.gov/files/federal-register/executive-orders/pdf/12866.pdf Accessed May 18, 2024.

Executive Order No. 13610. (2012). Identify and reducing regulatory burdens. In *Federal Register 77* 3 C.F.R. 93. U.S. Government.

Executive Order No. 13921. (2020). Promoting American seafood competitiveness and economic growth. Available at: https://www.presidency.ucsb.edu/documents/executive-order-13921-promoting-american-seafood-competitiveness-and-economic-growth

Executive Order No. 14094. (2023). Modernizing regulatory review. In *Federal Register 88*, *21* (p. 879). U.S. Government.

FAO. (2024). *The State of world fisheries and aquaculture 2024*. Blue Transformation in action. https://doi.org/10.4060/cd0683en

Farquhar, S. D., Sims, S., Wang, S., & Morrill, K. (2017). A brief answer: Why is China's aquaculture industry so successful? *Environmental Management & Sustainable Development*, *6*(1), 234. https://doi.org/10.5296/emsd.v6i1.11108

Foster, K. R., Vecchia, P., & Repacholi, M. H. (2000). Science and the precautionary principle. *Science*, *288*(5468), 979–980.

Froehlich, H. E., Couture, J., Falconer, L., Krause, G., Morris, J. A., Perez, M., Stentiford, G. D., Vehvilainen, H., & Halpern, B. S. (2020). Mind the gap between ICES nations' future seafood consumption and aquaculture production. *ICES Journal of Marine Science*, *78*(1), 468–477. https://doi.org/10.1093/icesjms/fsaa066

Garlock, T. M., Asche, F., Anderson, J. L., Eggert, H., Anderson, T. M., Che, B., Chávez, C. A., Chu, J., Chukuvane, N., Dey, M. M., Fitzsimmons, K., Flores, J., Guillen, J., Kumar, G., Llorente, I., Nguyen, L., Nielsen, R., Pincinnato, R. B. M., Sudhakaran, P. L., … Tveteras, R. (2024). Environmental, economic, and social sustainability in aquaculture: The aquaculture performance indicators. *Nature Communications*, *15*, 5274.

Genschick, S. (2011). *Pangasius at risk: Governance in farming and processing, and the role of different capital*. ZEF Working Paper Series Number 85. Center for Development Research.

Gibson, R. T. (1979). Red tape versus green light. *The Commercial Fish Farmer and Aquaculture News*, *5*(4), 12–14.

Guthrie, A. G., Barbour, N., Cannon, S. E., Marriott, S. E., Racine, P., Young, R., Bae, A., Lester, S. E., & Michaelis, A. (2024). Assessing socio-environmental suitability and social license of proposed offshore aquaculture development: A Florida case study. *Journal of the World Aquaculture Society*, *55*(1), 40–61. https://doi.org/10.1111/jwas.13031

Hahn, R. W. (1996). *Risks, costs, and lives saved. Getting better results from regulation*. Oxford University Press.

Häsler, B., Howe, K. S., & Stärk, K. D. C. (2011). Conceptualising the technical relationship of animal disease surveillance to intervention and mitigation as a basis for economic analysis. *BMC Health Services Research*, *11*, 225.

Hegde, S., Kumar, G., Engle, C., Hanson, T., Roy, L. A., van Senten, J., Johnson, J., Avery, J., Aarattuthodi, S., Dahl, S., Dorman, L., & Peterman, M. (2022). Economic contribution of the US catfish industry. *Aquaculture Economics & Management*, *26*(4), 384–413. https://doi.org/10.1080/13657305.2021.2008050

Hegde, S., Kumar, G., Engle, C., & van Senten, J. (2023). Cost of regulations on US catfish farms. *Journal of the World Aquaculture Society*, *54*(1), 32–53. https://doi.org/10.1111/jwas.12917

Helvey, M., Pomeroy, C., Pradhan, N. C., Squires, D., & Stohs, S. (2017). Can the United States have its fish and eat it too? *Marine Policy*, *75*, 62–67. https://doi.org/10.1016/j.marpol.2016.10.013

Herbeck, L. S., Krumme, U., Andersen, T. J., & Jennejahn, T. C. (2020). Decadal trends in mangrove and pond aquaculture cover on Hainan (China) since 1966: Mangrove loss, fragmentation and associated biogeochemical changes. *Estuarine, Coastal and Shelf Science*, *233*, 106531.

Hill, J. E., Tuckett, Q. M., & Watson, C. (2018). Court ruling creates opportunity to improve management of nonnative fish and wildlife in the United States. *Fisheries*, *43*(5), 225–230.

Hill, J. E., & Zajicek, P. (2007). National aquatic species risk analysis: A call for improved implementation. *Fisheries*, *32*(11), 530–538.

Hishamunda, N., Ridler, N., Bueno, P., Satia, B., Kuemlangan, B., Percy, D., Gooley, G., Brugere, C., & Sen, S. (2012). Improving aquaculture governance: What is the status and options? In R. P. Subasinghe, J. R. Arthur, D. M. Bartley, S. S. de

Silva, M. Halwart, N. Hishamunda, C. V. Mohan, & P. Sorgeloos (Eds.), *Farming the waters for people and food. Proceedings of the global conference on aquaculture 2010*, Phuket, Thailand, 22–25 September 2010 (pp. 233–264). FAO, NACA: Bangkok, Thailand.

Hurley, S. P., & Noel, J. (2006). *An estimation of the regulatory cost on California agricultural producers*. (Report). American Agricultural Economics Association.

Isen, A., Rossin-Slater, M., & Walker, W. R. (2017). Every breath you take—Every dollar you'll make: The long-term consequences of the clean air act of 1970. *Journal of Political Economy*, *125*(3), 848–902.

Johnson, K., Engle, C. R., & Wagner, B. (2014). Comparative economics of US catfish production strategies: Evidence from a cross-sectional survey. *Journal of the World Aquaculture Society*, *45*(3), 279–289.

Kaliba, A., & Engle, C. R. (2004). The economic impact of the catfish, *Ictalurus punctatus*, industry on Chicot County, Arkansas. *Journal of Applied Aquaculture*, *15*(1/2), 29–60.

Kaliba, A. R., Engle, C. R., Pomerleau, S., Hinshaw, J., & Sloan, D. (2004). The economic impact of the trout, *Oncorhynchus mykiss*, industry on Transylvania County, North Carolina. *Journal of Applied Aquaculture*, *15*(1/2), 61–83.

Kaplan, J. D., Johansson, R. C., & Peters, M. (2004). The manure hits the land: Economic and environmental implications when land application of nutrients is constrained. *American Journal of Agricultural Economics*, *86*(3), 688–700.

Kite-Powell, H., Rubino, M. C., & Morehead, B. (2013). The future of US seafood supply. *Aquaculture Economics & Management*, *17*(3), 228–250. https://doi.org/10.1080/13657305.2013.812691

Knapp, G., & Rubino, M. C. (2016). The political economics of marine aquaculture in the United States. *Reviews in Fisheries Science & Aquaculture*, *24*(3), 213–229. https://doi.org/10.1080/23308.249.2015.1121202

Krause, G., Brugere, C., Diedrich, A., Ebeling, M. W., Ferse, S. C., Mikkelsen, E., Agúndez, J. A. P., Stead, S. M., Stybel, N., & Troell, M. (2015). A revolution without people? Closing the people–policy gap in aquaculture development. *Aquaculture*, *447*, 44–55.

Kumar, G., Engle, C., Hegde, S., & van Senten, J. (2020). Economics of US catfish farming practices: Profitability, economies of size, and liquidity. *Journal of the World Aquaculture Society*, *51*(4), 829–846. https://doi.org/10.1111/jwas.12717

Kumar, G., Hegde, S., van Senten, J., Engle, C., Boldt, N., Parker, M., Quagrainie, K., Posadas, B., Asche, F., Dey, M., Aarattuthodi, S., Roy, L., Grice, R., Fong, Q., & Schwarz, M. (2024). Economic contribution of US aquaculture farms. *Journal of the World Aquaculture Society*, *55*(6), e13091. https://doi.org/10.1111/jwas.13091

Ledford, J. J., & Kelly, A. M. (2006). A comparison of black carp, redear sunfish, and blue catfish as biological controls of snail populations. *North American Journal of Aquaculture*, *68*(4), 339–347.

Lockwood, G. S. (2017). *Aquaculture: Will it rise to its potential to feed the world*. Blurb.

Mandel, M., & Carew, D. G. (2013). *Regulatory improvement commission: A politically-viable approach to US regulatory reform* (Vol. 3, pp. 1–24). The Progressive Policy Institute.

McClain, W. R., Romaire, R. P., Lutz, C. G., & Shirley, M. G. (2005). *Crawfish production manual*. Louisiana Cooperative Extension Service. Publication 2637.

McDorman, T. L., & Ström, T. (2006). Aquaculture and the multilateral trade regime: Issues of seafood safety labeling and the environment. In D. L. VanderZwaag & L. Chao (Eds.), *Aquaculture law and policy: Toward principled access and operation* (pp. 355–384). Routledge.

McGrattan, E. R., & Prescott, E. C. (2012). *The labor productivity puzzle*. Working Paper 694. Federal Reserve Bank of Minneapolis.

Metcalfe, M. R. (2002). Environmental regulation and implications for competitiveness in international pork trade. *Journal of Agricultural and Resource Economics*, *27*(1), 222–243.

National Center for Environmental Economics. (2014). *Retrospective study of the costs of EPA regulations: A report of four case studies*. Office of Policy, US Environmental Protection Agency.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, *591*(7851), 551–563.

NOAA. (2024). *Website repository of reports pertinent to marine aquaculture*. National Oceanic and Atmospheric Administration. https://www.fisheries.noaa.gov/national/aquaculture/aquaculture-library#key-documents

Noe, P. R. (2016). Smarter Regulation for the American Manufacturing Economy. Indiana University School of Policy and Environmental Affairs, US Manufacturing Public Policy Conference, National Press Club (Sept. 14, 2016).

Oidtmann, B. C., Thrush, M. A., Denham, K. L., & Peeler, E. J. (2011). International and national biosecurity strategies in aquatic animal health. *Aquaculture*, *320*(1–2), 22–23.

OMB. (1997). *Report to congress on the costs and benefits of federal regulation*. Office of Information and Regulatory Affairs, Office of Management and Budget, Executive Office of the President of the United States.

OMB. (2017). *2017 draft report to congress on the benefits and costs of federal regulations and agency compliance with unfunded mandates reform act*. Office of Information and Regulatory Affairs, Office of Management and Budget, Executive Office of the President of the United States.

OMB. (2024). *Report to congress on the benefits and costs of Federal Regulations and agency compliance with the unfunded mandates reform act. Office of Management and Budget, Office of Information and Regulatory Affairs. Fiscal years 2020, 2021, and 2022*. Office of Information and Regulatory Affairs, Office of Management and Budget, Executive Office of the President of the United States.

Osmundsen, T. C., Almklov, P., & Tveteras, R. (2017). Fish farmers and regulators coping with the wickedness of aquaculture. *Aquaculture Economics & Management*, *21*(1), 163–183. https://doi.org/10.1080/13657305.2017.1262476

Oster, S. M., & Quiglay, J. M. (1977). Regulatory barriers to the diffusion of innovation: Some evidence from building codes. *Bell Journal of Economics*, *8*(2), 361–377. https://doi.org/10.2307/3003292

Palmer, R. N., Cardwell, H. E., Lorie, M. A., & Werick, W. (2013). Disciplined planning, structured participation, and collaborative modeling-applying shared vision planning to water resources. *Journal of the American Water Resources Association*, *49*(3), 614–628.

Peel, D., & Lloyd, M. G. (2008). Governance and planning policy in the marine environment: Regulating aquaculture in Scotland. *Geography Journal*, *174*(4), 361–373.

Porter, M., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspective*, *9*(4), 97–118.

Primavera, J. H. (2006). Overcoming the impacts of aquaculture on the coastal zone. *Ocean and Coastal Management*, *49*, 531–545.

Reverter, M., Sarter, S., Caruso, D., Avarre, J.-C., Combe, M., Pepey, E., Pouyard, L., Vega-Heredia, S., Verdal, H., & Gozlan, R. E. (2020). Aquaculture at the crossroads of global warming and antimicrobial resistance. *Nature Communications*, *11*, 1870.

Rexroad, C., Rust, M. B., Riche, M., Wills, P., & Davis, M. (2021). Opportunities for US marine finfish aquaculture. *Journal of the World Aquaculture Society*, *51*(3), 501–508. https://doi.org/10.1111/jwas.12791

Rico, A., Phu, T. M., Satapornvanit, K., Min, J., Shahabuddin, A. M., Henriksson, P. J. G., Murray, F. J., Little, D. C., Dalsgaard, A., & Van den Brink, P. J. (2013). Use of veterinary medicines, feed additives and probiotics in four major internationally traded aquaculture species farmed in Asia. *Aquaculture*, *412*, 231–243.

Rubino, M. (2022). Policy considerations for marine aquaculture in the United States. *Reviews in Fisheries Science & Aquaculture*, *31*(1), 86–102. https://doi.org/10.1080/23308249.2022.2083452

Rubino, M. C., & Wilson, C. A. (1993). *Issues in Aquaculture Regulation* (p. 72). Bluewaters, Inc..

Rumley, E. (2010). *Aquaculture and the Lacey act*. An Agricultural Law Research Project, The National Agricultural Law Center.

Seafood Watch. (2020a). *Farmed oysters bottom and off bottom, worldwide*. Monterey Bay Aquarium.

Seafood Watch. (2020b). *US hybrid striped bass – Pond, tanks*. Monterey Bay Aquarium.

Seafood Watch. (2022). *US channel catfish - ponds*. Monterey Bay Aquarium.

Seafood Watch. (2023a). *US rainbow trout - raceways, ponds*. Monterey Bay Aquarium.

Seafood Watch. (2023b). *Clams, worldwide*. Monterey Bay Aquarium.

van Senten, J., Dey, M., & Engle, C. R. (2018). Effects of regulations on technical efficiency of US baitfish and sportfish producers. *Aquaculture Economics & Management*, *22*(3), 284–305.

van Senten, J., & Engle, C. R. (2017). The costs of regulations on US baitfish and sportfish producers. *Journal of the World Aquaculture Society*, *48*(3), 503–517. https://doi.org/10.1111/jwas.12416

van Senten, J., Engle, C., Senten, J., Engle, C. R., Hartman, K., Johnson, K. K., & Gustafson, L. L. (2018). Is there an economic incentive for farmer participation in a uniform health standard for aquaculture farms? An empirical case study. *Journal of Preventive Veterinary Medicine*, *156*, 58–67. https://doi.org/10.1016/j.prevetmed.2018.05.007

van Senten, J., Engle, C. R., Hudson, B., & Conte, F. S. (2020). Regulatory costs on Pacific coast shellfish farms. *Aquaculture Economics & Management*, *24*(4), 447–479. https://doi.org/10.1080/13657305.2020.1781293

Stead, S. (2005). A comparative analysis of two forms of stakeholder participation in European aquaculture governance: Self-regulation and integrated coastal zone management. In T. Gray (Ed.), *Participation in fisheries governance* (pp. 179–190). Springer Publisher.

Stigler, G. J. (1971). *The theory of economic regulations* (Vol. 2). The University of Chicago Press.

Sun, L., Engle, C. R., Kumar, G., & van Senten, J. (2023). Retail market trends for seafood in the US. *Journal of the World Aquaculture Society*, *54*(3), 603–624. https://doi.org/10.1111/jwas.12919

Thomas, D. (2012). *Regressive effects of regulation*. Mercatus Working Paper. Mercatus Center at George Mason University.

Thomas, M. H., & Hanson, T. R. (2007). Evaluating a new decision protocol with assurance bonding for releasing potentially invasive exotics: The case of the black carp (*Mylopharyngodon piceus*) in Mississippi. *Journal of Environmental Planning and Management*, *50*(1), 153–162.

Thunberg, E. M., Adams, C. M., & Cichra, C. E. (1994). Economic, regulatory, and technological barriers to entry into the Florida aquaculture industry. *Journal of Applied Aquaculture*, *4*(2), 3–14. https://doi.org/10.1300/J028v04n02_02

Tropical Aquaculture Laboratory. (2024). Special Local Needs permit. Available from the University of Florida at: https://tal.ifas.ufl.edu/extension-and-outreach/extension-publications/ Accessed June 16, 2024.

Tucker, C. S., & Hargreaves, J. A. (2008). *Environmental Best Management Practices for Aquaculture*. Wiley-Blackwell Publishing.

US Bureau of Labor Statistics. (2024). *Series ID CUUROOOOSAO, data tools: Databases, tables, & calculators by subject*. U.S. Government.

USDA-ARS. (2024). Subcommittee on aquaculture. United States Department of Agriculture Agricultural Research Service. https://www.ars.usda.gov/sca/

USDA-NASS. (2019). *Census of aquaculture 2018*. National Agricultural Statistics Service, United States Department of Agriculture. https://www.nass.usda.gov

USDA-NASS. (2024). *2022 census of agriculture*. National Agricultural Statistics Service, United States Department of Agriculture.

USEPA. (2004). *Technical development document for the final effluent limitations guidelines and new source performance standards for the concentrated aquatic animal production point source category*. EPA-821-R-04-012. Environmental Protection Agency, Office of Science and Technology.

USEPA. (2024). Clean Water Act, Title 33 Navigation and Navigable Waters, Chapter 26 Water Pollution Prevention and Control, §1365. Citizen suits. https://uscode.house.gov/view.xhtml?req=(title:33%20section:1365%20edition:prelim)

van Senten, J., Clark, C., & Engle, C. (In preparation). Regulatory costs on Atlantic Coast shellfish farms.

Walter, I., & Ugelow, J. L. (1979). Environmental policies in developing countries. *Ambio*, *8*, 102–109.

Wirth, F. F., & Luzar, E. J. (2001). Regulatory climate toward finfish aquaculture: The impacts of state institutional structure. *Aquaculture Economics and Management*, *5*, 99–114.

Wu, Y., Shan, L., Guo, Z., & Peng, Y. (2017). Cultivated land protection policies in China facing 2030: Dynamic balance system versus basic farmland zoning. *Habitat International*, *69*, 126–138.

Wui, Y.-S., & Engle, C. R. (2007). The economic impact of restricting use of black carp for snail control on hybrid striped bass farms. *North American Journal of Aquaculture*, *69*, 127–138.

Zajicek, P., Corbin, J., Belle, S., & Rheault, R. (2021). Refuting marine aquaculture myths, unfounded criticisms, and assumptions. *Reviews in Fisheries Science & Aquaculture*, *31*, 1–28. https://doi.org/10.1080/23308249.2021.1980767

Zivin, J., & Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, *102*(7), 3652–3673.

How to cite this article: Engle, C. R., van Senten, J., Hegde, S., Kumar, G., Clark, C., Boldt, N., Fornshell, G., Hudson, B., Cassiano, E. J., & DiMaggio, M. A. (2025). The National Regulatory Cost Burden on US aquaculture farms. *Journal of the World Aquaculture Society*, *56*(2), e70005. https://doi.org/10.1111/jwas.70005