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Ocean Food Systems and Hybrid Seafood Production: Transdisciplinary Case Studies of Cod, Eels, Salmon, and Lobster

Barry Antonio Costa-Pierce[1,2]

[1] Faculty of Biosciences and Aquaculture, Nord University, Bodø, Norway

[2] Ecological Aquaculture Foundation, LLC, Biddeford, Maine, USA

Correspondence: Barry Antonio Costa-Pierce, Ecological Aquaculture Foundation, LLC, Biddeford, ME., 04005, USA. Tel: 1-207-205-6566. E-mail: barry.a.costa-pierce@nord.no

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Abstract

Capture fisheries and aquaculture are researched, planned, and managed throughout the world as if they are independent entities ignoring their complex and evolving interdependencies. Global attention on "blue foods" as an important part of United Nations Sustainable Development Goals (SDGs) is focused on the restoration of capture fisheries and the sustainable expansion of aquaculture. Such a binary approach does not fit the current realities, opportunities, and innovations in ocean food systems (OFS), and does not integrate enough of the necessary transdisciplinary knowledge across professions. Integration of knowledge across professions is needed as modern ocean foods enter common marketplaces so interventions to increase sustainability must incorporate data on rural economic development, producers and their mixed ocean/land-based livelihoods and seasonal employment patterns, tourism, data on local to regional and global trade, and consumer behaviors. Four case studies detail the status and evolution of OFS typologies of American and spiny lobsters as fed fisheries, salmon as aquaculture-enhanced fisheries, and the capture-based aquacultures for cod and for eels. Objectives of this review were to examine for four OFS cases if there was adequate evidence to show that they were as productive, economically attractive, and as socially beneficial OFS that rival those of binary aquaculture or fisheries systems alone; and did they have significant potential to accelerate innovations as much as those sectors. For the four cases reviewed, productive, social and ecologically valuable, rapidly evolving OFS existed with demonstrable innovation trajectories. In the early part of this century it was estimated that capture-based aquaculture (CBA) accounted for about 20% of the total quantity of food fish production worth US$1.7 billion. Review of just four case studies having a limited number of participating countries found that annual value of the OFS exceeded US$4 billion: the value of eels as a capture-based aquaculture (CBA) was estimated US$2.3 billion for just two countries; for salmon as an aquaculture-enhanced fishery at $1.7 billion for only one state of the USA; and for lobsters as fed fisheries and a CBA, $825 million for the USA and Vietnam. However, OFS are disruptive as they require radically changed science, education, management, and development policies as current binary fisheries and aquaculture management approaches do not fit their current realities, or opportunities, or accelerate innovations, plus poorly integrate knowledge across professions. This was demonstrated by the example of dynamic management/regulatory situation for cod wild fisheries and the growing CBA for cod in Norway. The coming decades of accelerated climate and social changes will cause concomitant changes to ocean foods markets from local to global, and rural ocean foods livelihoods. These two systemic changes will drive the evolution and development of a greater diversity of OFS that will require much more attention of policy-makers and investors.

Keywords: ocean food systems, fisheries, aquaculture, capture-based aquaculture, aquaculture enhanced fisheries, fed fisheries, proto-aquaculture

1. Introduction

FAO (2012) stated that "Fisheries and aquaculture interact with increasing intensity as fishers shift from fishing to aquaculture and by competing in the same markets with similar products. The need to integrate planning and management of the two sectors seems vital to their future development and sustainability." Klinger et al. (2013) recognized that ocean food systems (OFS) of fisheries and aquaculture cannot be separated but are increasingly "hybrid seafood systems" whose products enter a common marketplace.

Aquaculture and fisheries systems dominate discussions in the assessments of the future of "blue foods" by international agencies, university centers, governments, non-governmental and philanthropic organizations

(Aguilar-Manjarrez et al., 2010; HLPE, 2014; SAPEA, 2017; Hoegh-Guldberg et al., 2019; O'Shea et al., 2019; Willett et al., 2019; Costello et al., 2020; CEA Consulting, 2020; Stuchtey et al., 2020; Blue Food Assessment, 2021; Crona et al., 2023). Few of these studies recognized the diversity of OFS, their system complexities, interactions in global-to-local marketplaces, or how they contribute to advancing mixed fisheries/aquaculture/land-based, rural livelihoods. Klinger et al. (2013) stated that the lack of data on OFS leads to mismanagement, miscommunication, lack of cross-pollination, with polarization and conflicts increasing, as occurring in the professional communities in aquaculture and fisheries (Belton et al., 2020; Zajack et al., 2020; Costa-Pierce et al., 2021; Sumaila et al., 2022).

Substantial price and volume competition occur between OFS products in the modern marketplace. Buyers at major global expos such as "Seafood North America" (Boston) or "Seafood Expo" (Barcelona) engage in the marketplace most strongly in the "white fish" market. If buyers cannot meet consumer demands for cod or haddock from capture fisheries, they purchase tilapia or pangasius catfish (*Pangasionodon hypophthalmus*) from aquaculture. Little et al. (2012) called some of these unrecognized interactions "white fish wars".

Recognition of the realities in OFS is important in complex social-ecological environments especially in rural areas and in common property resources. Incorporating human interventions in OFS will lead to a greater understanding of economically viable commodity production systems and give new insights into how societal choices can be oriented to achieve new, circular bioeconomies and the increased sustainability of natural resources (Defries et al., 2004).

2. Conceptual Framework: Typologies of Ocean Food Systems

2.1 Capture Fisheries

Capture fisheries are the capture and harvest of wild aquatic organisms where no interventions are made to manage or otherwise influence captured organisms by containment, feeding, or application of aquaculture techniques (O'Conner et al., 2011). Fish trapping is the capture of wild aquatic organisms for direct harvest using sedentary, non-mobile gears. Non-containment, fishery enhancement efforts to increase production are numerous. Artificial reefs and fish aggregating devices either aggregate or increase fish populations with impacts on overall production. Ocean structures can enhance fisheries in unexpected ways. Claisse et al. (2014) found that oil/gas platforms off California had the highest secondary fish production per unit area of seafloor of any studied marine habitat by about an order of magnitude. Platforms provided a "substantial amount of complex hardscape…distributed throughout the water column".

2.2 Aquaculture-Enhanced Fisheries and Capture-Based Aquaculture

A capture fishery that is sustained wholly or in part by the introduction of aquaculture organisms at early, recruitment or juvenile stages of a fishery using aquaculture hatchery/nursery systems to restock juveniles/seed into the ocean to produce harvestable adults in the wild is an aquaculture-enhanced fishery (AEF) (Figure 1).

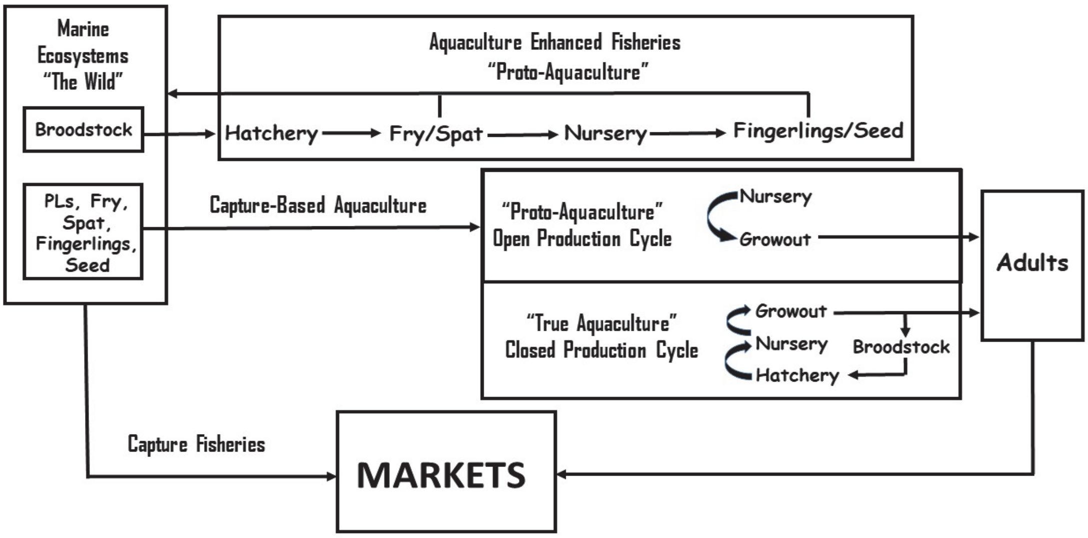

Figure 1. OFS connections between marine ecosystems ("the wild "), capture fisheries, capture-based aquaculture, aquaculture-enhanced fisheries, and markets (Costa-Pierce et al., 2022). True, "full cycle" aquaculture is a closed

production network where broodstock are selected from captivity and from genetic improvement programs that lead to domestication over time. There can be occasional replenishment of broodstock from the wild if adverse genetic issues arise, but the taking of large numbers of organisms from the wild is insignificant. Aquaculture-enhanced fisheries depend on the wild for broodstock and produce millions of juveniles/seeds in aquaculture hatcheries that are added to ocean ecosystems ("the wild") to sustain fisheries. Capture-based aquacultures take juveniles/seed from "the wild" and move them into aquaculture containment and grow-out systems.

A capture fishery that live harvests wild organisms at early stages in their life cycle and transports them to aquaculture systems for growout under confinement and management to mature, harvestable adults is a capture-based aquaculture (CBA) (Lovatelli and Holthus, 2008).

CBAs are very diverse and include rearing of finfish (tuna, groupers, etc.), many mollusks, and spiny lobsters in Asia. Recruitment overfishing due to the expansion of CBA is a concern for long-lived, K-selected species. R-selected species generally have high growth rates, reach sexual maturities at younger ages, have smaller body sizes, and relatively rapid population turnovers. K-selected species grow slower, reproduce at older ages, live longer, and have a wide age diversity in their populations (Ricklefs, 1979).

CBA uses the knowledge of the "aquaculture toolbox" to: (1) bring wild juveniles/seed into captivity and acclimate them to containment and feeding, (2) give high quality care, ameliorate stress, provide advanced health and welfare, (3) implement disease prevention, diagnosis, and treatment, and (4) employ advanced, humane slaughtering and rapid delivery to markets. FAO (2007) has developed additional criteria to guide CBA that include: by-catch should be avoided or eliminated; additional habitat damages should not occur; recruitment of juveniles should not lead to recruitment overfishing; capture of juveniles should not disadvantage other resource users; and CBA production should offset any losses in capture fisheries yields.

CBA production is not reported as a separate category in global summaries (Klinger et al., 2013). In the early part of this century CBA was estimated to account for about 20% of the total quantity of food fish production worth US$1.7 billion (Ottolenghi et al., 2004). The few economic studies of CBAs found higher values due to better product qualities for milkfish in the Philippines (Gonzales, 2006), amberjack in Japan (Ottolenghi et al., 2004), and grouper in Thailand (Boonchuwong and Lawpong, 2002). Jeffs and Hooker (2000) examined the economics of CBA for spiny lobsters in a land-based facility in New Zealand. For CBA species that require modifications of vessels, gears and onshore facilities such as tanks, pumps, and management changes, CBA is costly. Hermansen and Dreyer (2008) list ways to increase revenues by increasing yields, improving product qualities, differentiating sizes to increase pricing possibilities, providing year-round supplies, and avoiding unfavorable natural conditions. Increased revenues can offset costs to make CBAs more attractive over conventional fisheries.

2.3 Proto- and "True", Closed Cycle Aquaculture

It is widely accepted that aquaculture arose multiple times in societies as an evolution from capturing and trapping fish, to holding and keeping fish, and to reproducing, growing, and domesticating fish (Balon, 1995; Atlas et al., 2020; Beveridge and Little, 2002; Costa-Pierce, 2022). Beveridge and Little (2002) defined "proto-aquaculture" as "activities designed to extract more food from aquatic environments, such as: the transplantation of fertilized eggs, entrapment of fish in areas where they could thrive and be harvested as required, use of environmental enhancements such as development of spawning areas, enhancement of food, exclusion of competitors or predators, and containment of fish and shellfish in systems (ponds, cages, pens) until they increased in biomass or until their value had improved". They distinguished "proto-aquaculture" from aquaculture due to the small degree of control over the life cycle of an aquatic species and the low impact of interventions on aquatic production.

Aquaculture is defined as aquatic farming to enhance production as regular stocking, feeding, protection from predators, plus individual, community, organization, or corporate ownership of stocks (Rana, 1998). Aquaculture is very diverse today comprising the husbandry of over a hundred species in fed or unfed systems growing domesticated and non-domesticated species with hatcheries. Anderson (2002) stated that the difference between fisheries and aquaculture was based on the degree of property rights, and that modern fisheries and aquaculture systems were differentiated more on the applicability of property rights given to harvesters by management entities. "True" aquaculture is a specific typology of OFS, a closed aquaculture production network having little/no connection to the "wild" (Figure 1).

3. Case Studies of Ocean Food Systems

Four cases were chosen for interpretation to illustrate OFS typologies and their social-ecological importance (Table 1).

Table 1. Estimated Production and Values for Typologies of Ocean Food Systems (OFS)

OFS	Typologies	Locations	Estimated Production (MT); Values (US$)	References
Cod	Unfed Fishery (UF) CBA	Norway	193,000; 371 million 6,000; 30 million	Hermansen (2017); Sogn-Grundvåg et al. (2021); Pettersen et al. (2023)
Eels	CBA	USA (ME) China	4535 kg; 20 million 222,000; 2.1 billon	Maine DMR (2022) Yuan et al. (2021)
Salmon	AEF	USA (AK)	393,000; 1.7 billion	McDowell Group (2020); Brenner et al. (2022)
Lobster	Fed Fishery CBA	USA (ME) Vietnam	49,000; 725 million 1100; 100 million	Maine DMR (2020, 2023) MARD (2007); Utama et al. (2021)

Notes: CBA= capture-based aquaculture. AEF= aquaculture enhanced fisheries. ME= United States state of Maine. AK= Unites States state of Alaska. MT= metric tons.

Through interpretive analysis of selected case studies assumptions can either be supported or challenged. Tellis (1997) states that case studies are valuable where there are limitations of quantitative methods that provide holistic, controversial explanations of real-world issues. Weichselgartner and Truffer (2015) point out the value of case studies using transdisciplinary approaches to obtain an integrated understanding of complex problems by gathering a diversity of perspectives. The four case studies were chosen to demonstrate the divergence of OFS from binary aquaculture and fisheries systems and their unique systems evolution and future potentials.

3.1 The Evolution of Cod (Gadus morhua) *as A Capture-Based Aquaculture in Norway*

In commercial fisheries, large biomasses are harvested in designated fishing zones with strict regulations on quotas, gears, seasons, species, sizes, sexes, and habitats, among others. In some ocean regions, stocks of cod are so depleted that they become a "choke species" (Mortensen et al., 2018). Traditional fisheries do not store fish alive. There is no containment. Significant seasonal swings in volumes and prices occur causing economic downturns. Large amounts of fish have limited quality and shelf-life and fetch lower market prices, especially in fresh fish markets.

Conventional cod capture fisheries vessels in Norway receive an annual cod quota. Over the last 30+ years the cod quota had fluctuated dramatically from highs of 475,000 MT (2013-14) to alarming lows of around 100,000 MT in 1990-91 (Svåsand et al., 2000; Hermansen, 2017). Lately, the overall fisheries quota for cod has decreased (The Fishing Daily, 2022).

After reviews and pilot investigations of the feasibility of the capture-based aquaculture (CBA) for cod, this innovation was introduced in Norway in 1980, along with a new, temporary regulatory system (Dreyer et al., 2008). A new quota system was created for cod: one for interests fishing conventionally, and another for the capture-based aquaculture (CBA) of cod (called the "cod bonus" system). In CBA, cod are caught conventionally, sorted by quality, and those fish deemed to be suitable for aquaculture are put into containment. Most participating cod fisheries are allowed to retain cod alive for only up to 12 weeks. A "deviation permit" option exists to aquaculture cod for a longer period of time but few licenses have been granted (Hermansen, 2017).

The CBA "quota bonus system" remains temporary. It is tied to the overall annual capture fisheries quota for cod and evaluated regularly. Fisheries regulators first offered a 20% increase in quota for captured fish destined to enter CBA. The bonus has been as high as 50%. Thus, cod fishing vessels can, in principle, double their catch; however, due to damages from capture and handling, not all cod are suitable for CBA after capture (Hermansen, 2017; Sogn-Grundvåg et al., 2021). For 2023, the CBA bonus has been lowered to 40% (The Fishing Daily, 2022). Hermansen (2017) states that, although the CBA of cod has been present in Norway for decades, that: "It's still in the early stage with actors involved being the pioneers.", and that: "It remains to be seen whether CBA for cod can survive without the quota bonus". Pettersen et al. (2023) concluded that, with an average price premium of 26% for CBA cod compared to wild cod, combined with reductions in the CBA quota bonus, that this price premium was “not sufficiently large to incentivize further development of the CBA branch of the Norwegian cod industry.”

CBA offers the potential for a win-win for both cod fishing industries and consumers. Although only about a dozen commercial fisheries are involved to date, in 2016, the largest CBA landings of cod, more than 6,000 MT, were recorded, increasing from 2,000 MT in 2013 (Hermansen, 2017). CBA allows fishing companies to spread the supply of cod throughout the year. Cod catches are highest in the January to April period when the highest quality fish, the famous “Skrei”, migrate from the high Arctic to spawn in the region around Lofoten, Norway. Unpredictable ocean conditions due to climate change and unpredictable landings have occurred in recent years as cod stocks moved north from the Lofoten islands region.

Cod supplies are very limited during the summer months. Cod is an “elastic” commodity (Case et al., 2012); when seasonal supplies increase, fish prices fall, and vice-versa. Ashrafi et al. (2020) found that large cod harvests and oversupply in the spring caused economic losses by reduced prices that were so large that they offset all other economic benefits from cost reductions in the fishery. Cod from CBA has higher value due to its higher quality (Hermansen, 2017). CBA provides the ability to spread higher quality, higher priced fish supplies out over the summer months. The volume of CBA cod is small; thus summer markets remain strong allowing for higher profitability.

With CBA, marketing could be shifted towards consumer-driven demand. Sellers could enter into agreements with buyers before the fish are harvested, enabling longer-term planning for both parties and increasing the bargaining power for the supplier. Thus, cod from CBA could also be more accessible, as it can be slaughtered, processed and transported in accordance with consumer needs (Hermansen, 2017).

There remain numerous challenges and opportunities to increasing the adoption and increased profitability of CBA for cod in Norway (Hermansen, 2017; Sogn-Grundvåg et al., 2021; Pettersen et al., 2023) that are instructive for the development of other CBA globally:

(1) High capital and operating costs are incurred to modify fishing vessels and build the required aquaculture infrastructure for CBA. Live fish holds needed to ensure good fish survival take up fishing vessel cargo space thus decreasing the size of harvest loads.

(2) Fishing vessels must moor at both the aquaculture site and the processing plant, resulting in additional steaming time, pumping costs, and increasing electric use, thus increasing carbon emissions, operations that conflict with Norwegian national policy goals (Sogn-Grundvåg and Hermansen, 2022). Development of CBA sites close to fish processing plants could ameliorate these issues, but competition for sites and regulations on both land and water use are significant barriers.

(3) Innovations in cod aquaculture made over the past decades in aquaculture engineering, containment systems, disease prevention, management and control, and designer feed formulations could enhance significantly cod CBA (Puvanendran et al., 2021). High mortalities occur during the first few days after capture but decline rapidly. Weight losses are reported at about 1%/week (Hermansen, 2017). These could be turned into weight gains by refining feed qualities and quantities well known in aquaculture (Puvanendran et al., 2021). Aquaculture innovations would allow longer-term culture than 12 weeks and extend the market to take advantage of higher summer prices. Accelerated investments in veterinary services would investigate the science of possible disease transfers, especially the risk of VHS (viral hemorrhagic septicemia) transfers from CBA cod slaughtered at traditional harvesting plants, and how to treat any water discharges at both sites that may be in proximity.

3.2 American Eels (Anguilla rostrata)*: Fishery to Capture-Based Aquaculture*

American eels are native to the Atlantic coast of the Americas from Venezuela to Canada (Don and Carlson, 2019). They are catadromous, spawning in the Sargasso Sea and migrating to become adults in freshwater rivers, lakes, and ponds. Eels are best known for their economic value as sushi which has become popular globally. They are less widely recognized as one of the world’s largest and most valuable CBAs for the sale of glass eels (elvers), a transitional larval stage seen during their migration from the Atlantic Ocean to freshwaters.

Wild caught elvers from fisheries account for an estimated 90-95% of current global eel aquaculture production (FAO, 2020). The multi-billion-dollar intensive eel aquaculture systems in Asia (China/Taiwan, Korea) are dependent on wild elvers from the Atlantic Ocean. The US state of Maine is the largest provider as about 90% of its elvers go to Asia. In Europe elvers were consumed directly (Spain, Portugal); however, that trade has become insignificant with the market substitution of “gulas” (a surimi-type product that mimics baby eels).

Approximately 2.5 kg of elvers are required to produce a metric ton (MT) of market-sized eels. The USA exports wild elvers then imports about 90% of eels it consumes from Asia. US eel imports from Asia have increased to about 476 MT worth an estimated US$58 million (Cook, 2018).

CBA of eels has developed into an important socio-economic, rural development model in Maine, USA. Impacts scope from local to global: (1) The existing elver fishery is well managed and provides large socio-economic and livelihood benefits for fishing families in poverty-stricken and Indigenous rural areas where few alternatives to earn incomes exist, and (2) Hatchery technologies for eels are expensive, unreliable, difficult to manage, and have failed in countries like South Korea (Frost et al., 2000; Cook, 2018).

Eel hatchery research is continuing and has been on-going for many decades, especially in Japan (Yuan et al., 2021). It has been stymied repeatedly (Don and Carlson, 2019) by the challenges of spawning and rearing from leptocephali to the elver stage in captivity because: (1) Eels do not mature spontaneously, sexual maturation of eels is driven by a complex set of environmental cues; (2) Most farmed eels turn out to be males; markets want larger females; (3) Hormonal treatments have been developed and reliable supplies of fertilized eggs can be obtained but few healthy larvae result; (4) Development of leptocephali to glass eels takes 250-300 days in culture versus 110-160 days in the wild, and survival rates are very low <10%; (6) Leptocephali feed on marine snow in nature (Miller et al., 2020) but in a hatchery setting the only effective feeds are formulations of expensive, thick, pinkish pastes made primarily of shark eggs, soy protein, and vitamins, and these are very expensive and cause water quality problems; and (7) Light-wary leptocephali need to be kept in darkened rooms making hatchery management difficult and costly.

In Maine, elver fisheries are well-managed with a limited entry quota system providing significant social-ecological benefits to fishing and Indigenous families scattered over a large rural area. With prices fluctuating from US$1,156 (2020) to US$5,212/kg (2018); elvers are valued at US$4,696/kg in 2022. Elvers are the second-most valuable fishery behind American lobster. A dealer-to-dealer swipe card and elver exporter license are required which allow effective tracking of elvers at all points in the chain of custody, an innovative and critical part of the effective management of this CBA.

The US Atlantic State Marine Fisheries Commission (ASMFC) regulates the cross-boundary state fisheries and elver harvests from two US states (Maine, South Carolina) for the American eel. In 2019 it implemented "Addendum V" that modified elver regulatory provisions to add a 90.7 kg (200 pound) limit for elvers to be used for the development of domestic aquaculture facilities. This amount was added to Maine's existing elver quota (ASMFC, 2020). An entrepreneur has used some of these elvers to initiate a start-up eel aquaculture operation (American Unagi, 2023).

3.3 Alaska Salmon (Oncorhynchus spp.)*: An Aquaculture-Enhanced Fishery (AEF)*

AEFs for Pacific salmon have grown rapidly throughout the North Pacific. New AEF hatcheries have been added each year from 2000 throughout Kamchatka (Russian Republic), North and South Korea, and Japan. Almost all of the chum salmon (*Oncorhynchus keta*) in Japan are now produced in hatcheries (Bemish and Neville, 2021).

Alaska (AK) prohibits salmon aquaculture, but economically vital salmon AEF exist in three fishery regions (Southeast AK, Prince William Sound, Lower Cook Inlet). About 41 million hatchery salmon were added from these regions to the ocean in 2021 (Brenner et al., 2022). An estimated 31% of harvested salmon in Southeast, 28% in Prince William Sound, and 15% in the Westward Region originated from hatcheries. McNair (2000) estimated that 65% of chum, 30% of pink, and 22% of coho salmon caught in AK came from hatcheries, including 94% of the pink salmon caught in Prince William Sound. There are 25 private nonprofit hatcheries operating in AK.

AEF is funded by a tax on sales of returning fish. Further south in the USA, the Columbia River Basin has 25 hatcheries releasing about 120 million juveniles/year which contribute to an estimated 50-70% of salmon fisheries. Washington State has more than 90 rearing facilities. Oregon operates 34 hatcheries and 15 other rearing facilities.

According to Beamish and Riddell (2009) billions of hatchery salmon are added to a "common feeding area" of the northern Pacific Ocean, and that success of hatcheries is driven by interactions of fish with marine ecosystems. Bemish and Neville (2021) have shown that adding more aquaculture hatchery fish does not improve fisheries productivity. Ocean carrying capacities and large-scale climate changes limit production, not the number of juvenile fish added. The critical factor to production appears to be the amount of juvenile growth experienced in the first months after their release to ocean ecosystems.

3.4 Spiny (Panulirus homarus) *and American* (Homarus americanus) *Lobsters: Capture-Based Aquaculture, Fed Fisheries and Proto-Aquacultures*

In Vietnam, Indonesia and Malaysia, farming of marine fish and lobsters in cages is a CBA (Utama et al., 2021). There are major environmental and human health concerns but also large economic benefits for rural fishing families. Juvenile lobsters and fish (mainly cobia, groupers, snappers) are caught at coral reefs and fed with fisheries byproducts to reach market sizes. Production has been estimated at 1,340 MT/year of spiny lobsters and 6,660 MT tons of fish (Hedberg et al., 2017). Antibiotic use is high (Hedberg et al., 2018). In Indonesia, puerulus larvae of *Panulirus homarus* were observed to settle in seaweeds. They are harvested by fishermen and exported or stocked into floating net cages and fed with "trash fish". Bahrawi et al. (2015) estimated more than 600,000 puerulus larvae were caught in 2008-2009

American lobster fisheries in New England and Atlantic Canada are a "fed fishery", the largest "proto-aquaculture" in the world. Lobster landings in Maine, USA grew from 1997 to 2009 from 21,000 MT to 34,000 MT/year, two to four times the 40-year average of 9,000 MT/year from 1950 to 1990 (Maine DMR, 2010). Lobster landings in Maine account for 90% of the state's total fishery value, employ over 5,000 families, and are an essential contributor to the rural economy. Zou et al. (2021) found that the revenue/lobster vessel in 2011 was US$ 155,425, and that all size classes of lobster vessels on average earned a net profit. After boom years in 2016 (59,874 MT) and 2018 (54,903 MT), yields have dropped significantly in 2022 to 44,434 MT (Maine DMR, 2023). However, in 2021 demand skyrocketed and so did prices, reaching US$14.80/kg, the highest ever recorded. Prices dropped back in 2022 to US$8.75/kg.

Wild herring, alewife, menhaden and other fish are used as unprocessed feeds ("baits") added directly to wire traps to catch lobsters. "Baits" are "feeds". A quarter to a third of lobster landings may be due to fish inputs (Salia et al., 2002). Grabowski et al. (2010) found inputs of "baits" increased lobster growth by 15% and estimated that the 60,000 MT of "baits" added to lobster traps resulted in an additional 5,000 MT of lobster production, a crude food conversion ratio higher than beef production (Hilborn et al., 2018).

The "bait" industry is a very large sector feeding the lobster industry and the rural economy. Approximately 100,000 MT/year of herring are landed in New England and about 70% are used as lobster feeds. In 2022, Maine, being the largest of all New England lobster fisheries, reported that a total amount of 13,426 MT of alewives, herring and menhaden was landed commercially and used for lobster "bait", valued at US$15.5 million (Maine DMR, 2023). This landing price for lobster "baits" (US$1,154/MT) is less than the February 2023 world market price for fish meal (US$1,762) (The Global Economy, 2023). The yearly input of "bait" per unit area of inshore waters of the Gulf of Maine is about 85 kg/ha, a yield comparable to a productive marine fishery (Salia et al., 2002).

Lobster trap densities have increased almost four-fold over the last two decades. "Bait" use has increased, but few reliable data is available. Harnish et al. (2009) estimated the amount of "bait" required to catch a lobster weighing about 480 g ranged from 185 g (November) to 1,455 g (April), the fishing season in Atlantic Canada. They estimated the overall ratio of "bait"/catch to be about 1.9. Jury et al. (2001) conducted video monitoring of lobster traps and found that "baits" were eaten inefficiently, or not eaten at all by lobsters. Over 90% of lobsters caught initially in traps escaped.

4. Discussion

Global initiatives in "circular, blue bioeconomies" have led to important assessments of cultured and harvested marine resources (European Commission, 2020). "Wastes" become resources for valuable product creation. Salmon wastes comprise 41.5% of total biomass (Stevens et al., 2018). Lobster wastes are 50-70% of biomass with disposal costs estimated at US$7.5 million/year (Nguyen et al., 2017). Salmon mortalities in Scotland are about 7% of yearly production with disposal cost of about US$2.7 million/year (Stevens et al., 2018). Innovative regulations such as the EU landing obligation, a 5-year commitment to land all harvested marine species for regulated fish stocks have stimulated innovations. Iceland prohibits discards of fisheries bycatch and provides incentives for compliance. Juvenile fish can be separated from other catches and only 50% is withdrawn from the quota. The remainder of the bycatch can be sold at auction markets at a maximum 5% of the total catch on average. The price a vessel gets for the bycatch is distributed where the crew gets 20% of the value and 80% goes to a public fisheries project fund. Landed bycatch has also fueled a national fishmeal and fish oil industry expanding aquaculture opportunities.

New markets for products derived from what were once considered wastes change value propositions for capture fisheries as byproducts prove more valuable than their food values. Among the most advanced of these are *Benecta*, a supplement developed in Iceland from northern shrimp (*Pandalus borealis*) shells whose value is higher than the shrimp as food. Such developments can lead to an almost complete reorganization of thinking and industry developments towards diversification of fishing companies from "food only" fisheries into "biomass/zero waste" fisheries expanding product offerings and accelerating values while being more sustainable. OFS innovations can lead to a complete redesign of fishing boats to incorporate on board processing for not only food products but also for an expanded variety of high value products landed all at once; an example of this exists in Norway (Verselannas; Johan Johansen, Norwegian Institute of Bioeconomy Research, personal communication). OFS innovations can move fishing away from trawling only to diversification to purse seining, trapping, and other means of live hauling that produce high quality, high value, fresh products.

The Norwegian Ministry of Fisheries and Coastal Affairs founded a National Centre of Excellence in CBA at NOFIMA, Tromsø with a focus on cod, but is also investigating the feasibilities for the CBA for crabs and other marine species. To sustain cod supply year-round and ameliorate losses, NOFIMA developed methods to live catch, acclimatize, and feed wild cod. This Norwegian National Centre is the first and only known center in the world focused on OFS, or "hybrid seafood" (Klinger et al., 2013) systems that have been shown to produce large, globally important economic benefits. CBA research examines efficiencies and improvements in value chains that CBA can make, but close cooperation (and openness to new ideas) between fishing and aquaculture industries, regulatory/management, and research institutions is required.

There are many parts of the world where development of OFS of CBA, AEF and fed fisheries may be the preferred typologies over binary capture fisheries and aquaculture alone due to the shortcomings and expense of the required technologies, and their socio-economic, livelihood and rural development suitabilities. Case studies of eels, salmon, cod, and lobsters reviewed here demonstrate their high productivities, evolving management regimes, and high socio-economic values to rural economies. They are instructive to other developing ocean food economies; for example, to India, where hatchery technologies for many marine species of high market value have not been successful, and CBA may be the best rural development opportunity (Athithan, 2020). However, all OFS typologies have a future only if serious environmental concerns regarding waste and chemical use are eliminated.

5. Conclusions

There are calls from organizations throughout the world for humanity to derive more human foods from and produce less waste to oceans. Modern OFS cannot be defined simply as capture fisheries or aquaculture but their research, data collection and management systems work as if they do. While most of the cases reviewed here have been considered previously, and pilot projects date as far back as the 1800's, e.g. for CBA in Norway (Hermansen, 2018), broad global recognition, research and expansion of OFS is new and needs much more serious social-political-regulatory and scientific investigations. OFS have the possibility to spur innovations that could change the trajectory of both traditional capture fisheries and full-cycle aquaculture.

Innovations in capture fisheries technologies and management regimes and costly, full cycle aquaculture are not the only options for expanding food production from the oceans. The panoply of system innovations present in both the aquaculture and fisheries "toolboxes" could be blended to produce a larger number of innovations in the OFS space that, some cases, could contribute more to sustainable fisheries livelihoods, environmental restoration, and coastal economies than just fisheries and aquaculture alone, as demonstrated here by the benefits of CBA of cod, eels, and lobsters. The AEF for salmon stands out as an additional, very dynamic area for further OFS investigations as more attention is being paid to conservation hatcheries (Downeast Salmon Federation, 2023), rewilding and adult supplementation efforts (Naish et al., 2007; Clarke et al., 2016).

Additional billions of dollars have been proposed to develop aquaculture, sustain, and restore capture fisheries to meet sustainable development goals (SDGs). There are alternative OFS options to consider that may better meet a greater number of the SDGs in rural economic development, local to global value chains, trade, and innovations (production, trade, consumption, culture, human and animal health, waste, and environmental impacts). There are opportunities in OFS to better utilize data to analyze and reform governance structures to improve the modern, mixed, ocean livelihoods of fishing communities. A much greater recognition of the diverse opportunities for capture-based aquaculture, aquaculture-enhanced fisheries, fed fisheries, and biomass fishing is essential to the development of sustainable, blue bioeconomies.

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