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Integrated multi-trophic aquaculture of steelhead trout, blue mussel and sugar kelp from a floating ocean platform

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ABSTRACT

Over the last several decades, the commercial fishing fleet in New England has been subjected to increasingly restrictive management measures established to rebuild declining stocks. This has limited fishing opportunities and significantly reduced the inshore small vessel fleet. To help support New Hampshire (NH) commercial fishermen, an extension program was developed by the University of New Hampshire (UNH) and NH Sea Grant to train fishers on small-scale integrated multi-trophic aquaculture (IMTA) growing steelhead trout, blue mussels, and sugar kelp together, with the goal of providing alternative income sources and increasing local food production without adding significant levels of nitrogen to the environment. A total of 416 kg of steelhead trout, 3072 kg of blue mussels, and 638 kg of sugar kelp were produced in this study. The steelhead trout released an estimated 25.1 kg of N into the environment, while the mussels and kelp together extracted an estimated 41.5 kg N for a net reduction of ~16.4 kg N from the ecosystem. There was no observed negative impact on local water quality at any point during the trial. Overall, this program demonstrated a culture method that can positively impact the ecosystem, while providing the fishermen with a new skill set that they could adopt either part time or full time, to provide additional income.

1. Introduction

Aquaculture accounted for 49% of total fish and shellfish production for human consumption in 2020 (FAO, 2022). Aquaculture remains the fastest growing animal food production sector, largely due to global fish consumption increasing nearly twice as quickly as annual world population growth (FAO, 2022). Asia is by far the largest aquaculture producing region in the world, accounting for 89% of the total volume of fish produced in the last 20 years. Global capture fisheries production declined from its peak of 96.5 million tons in 2018, to 90.3 million tons in 2020 (FAO, 2022). As a general trend, capture fisheries production has largely plateaued since 1986, with many wild capture species in decline (FAO, 2022).

Fishers around the world face many challenges including strict regulation, increased fuel cost, price fluctuation, declining stocks and impacts of climate change (Fernandez et al., 2015). In the Northwest Atlantic, where this study took place, Atlantic salmon and Atlantic cod, the two major historic fisheries collapsed in the 20th century forcing many fishers to transition out of the industry (Milich, 1999; Dadswell et al., 2022). These limitations have led to a drastic reduction in the inshore small vessel fleet and contributed to the large United States seafood trade deficit.

Some fishers are transitioning to aquaculture to supplement their income. The skills and equipment required for fishing are easily transferrable to aquaculture. The largest impediments to aquaculture growth are startup cost and environmental regulations (Skladany et al., 2007; Tisdell et al., 2010; Young et al., 2019). Fish farming releases nutrients to the environment causing hyper-nitrification (Gowen and Bradbury, 1987; Qi et al., 2019; Quimpo et al., 2020). This negative impact of aquaculture derives mainly from particulate and dissolved nutrients from animal excretion and uneaten food (San Diego-McGlone et al., 2008; Quimpo et al., 2020). This has raised concerns from environmentalists and other stakeholders.

For this project, an alternative aquaculture model was designed that would emphasize small-scale production closer to shore. It was reasoned that these smaller systems would be more affordable and user friendly for fishers. To address the concern of nitrogen loading in an already impaired area where the project was to take place, the Piscataqua River in coastal NH, we decided to use an integrated multi-trophic aquaculture (IMTA) farming system. In IMTA, the culture of a fed product (i.e., fish)

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is combined with the culture of organic and nonorganic extractive species that bio-mitigate nutrients from the farm and surrounding waters. IMTA promotes economic and environmental sustainability by converting byproducts and uneaten feed from fed organisms into harvestable crops, thereby reducing eutrophication, increasing economic diversification, and being more socially acceptable (Neori et al., 2004; Troell et al., 2003; Tournay, 2006; Buck et al., 2018). The concept of developing an "environmentally clean" aquaculture, based on the integrated culture of fish, mollusks and macroalgae, was first proposed by Gordin et al. (1981). The system was subsequently tested (Gordin, 1982; Gordin et al., 1990; Shpigel et al., 1991) and further developed (McDonald, 1987) with shrimp and oysters in land-based facilities (Wang, 1990; Wang et al., 1990). More recently, IMTA has been investigated extensively in Atlantic Canada with Atlantic salmon (*Salmo salar)*, blue mussels (*Mytilus edulis*) and kelp (Neori et al., 2004; Ridler et al., 2006, 2007; Robinson et al., 2007). However, uptake efficiency in open-water IMTA is still debated (Reid et al., 2007; Fang et al., 2016; Zhang et al., 2019).

For this study we focused on steelhead trout (*Oncorhynchus mykiss*), blue mussels, and sugar kelp (*Laminaria saccharina*). Steelhead trout are an anadromous salmonid species native to the North Pacific Ocean, ranging from southern California through Alaska. Steelhead trout are born as rainbow trout but migrate to the ocean as juveniles and spend their adult lives at sea before returning to freshwater to spawn. Steelhead trout typically grow larger and faster than the entirely freshwater counterpart, rainbow trout (Kendall et al., 2015). They require cool (optimal temperature is 9–15 °C), oxygen rich waters with high flow rates (Myrick and Cech Jr, 2005). Steelhead trout can grow to 7–10 kg within 3 years, command a premium price, and feed conversion ratios (FCRs) as low as 1.0–1.2 have been achieved, making it an excellent species for aquaculture (Boydstun and Hopelain, 1977; Masser and Bridger, 2007; Bai et al., 2022; Kause et al., 2022).

Blue mussels have a large range covering most of the North Atlantic and Mediterranean and are cultured around the world (De Witte et al., 2014). They are benthic filter feeders that can process large amounts of water and show selective preference for specific food sources (De Witte et al., 2014). Blue mussels are known to consume and assimilate uneaten particulate fish feed as well as fish feces (Reid et al., 2010; Handå et al., 2012). Studies have reported improved growth of mussels grown in proximity to fish cages (Stirling, 1995; Wallace, 1980), however others have not found such findings (Taylor et al., 1992; Cheshuk et al., 2003; Navarrete-Mier et al., 2010; Handå et al., 2012).

Sugar kelp are a macroalgae native to the Western Atlantic. They are the base of many food webs and provide ecosystem services including creating habitat, sequestering carbon and nitrogen, and shoreline protection (Dayton, 1985; Bartsch et al., 2008; Falkenberg et al., 2012; Efird and Konar, 2014; Trebilco et al., 2015). Sugar kelp is a historically important food source for coastal populations, and in recent years has gained favor as an aquaculture species for food, biofuel, and various chemical compounds (Bjerregaard et al., 2016; Hwang et al., 2019; Goecke et al., 2020). Sugar kelp can remove between 38 and 180 kg nitrogen and 1100–1800 kg C per hectare making it an effective tool for climate change mitigation and alleviating eutrophication (Yarish et al., 2017). Kelp growth is largely limited by light and nutrient availability, and improved growth rates have been observed when kelp is grown in proximity to fish and mussel farms (Handå et al., 2013; Hargrave et al., 2022).

To encourage NH fishers on small-scale IMTA, extension programs were developed through the Saltonstall Kennedy program and NH Sea Grant. These programs enabled local fishers to participate in and learn small-scale integrated aquaculture of steelhead trout, blue mussel and sugar kelp grown. With this experience, fishers can determine if IMTA will be a suitable business alternative to fishing full time.

2. Materials and methods

2.1. Site selection

The culture site was at the mouth of the Piscataqua River, approximately 400 m off the coast of New Castle Island, New Hampshire in 9 m of water at the mid-tide. This site was chosen due to its proximity to the University of New Hampshire Judd Gregg Marine Research Pier (JGP). The culture site was characterized by minor freshwater input from the river (mean salinity of 30), high velocity currents (up to 2.3 m/s), large twice-daily tides of ~3 m, heavy boat traffic, and strong wave action (Bilgili et al., 1997).

2.2. Cage technology

A platform composed of two high density polyethylene (HDPE) cages (Fig. 1) was moored between two 750 kg Jeyco Stingray drag embedment anchors (Jeyco, 7B Townsend Street, Malaga, Western Australia). Each anchor line was 30 m long, made from 5 cm diameter Polysteel line and shackled to an upper bridle on either side of the fish cages. Each of the two cages measured 4.5 × 4.5 m, had a net depth of 3.5 m, and a volume of 68 m^3. The nylon nets had a mesh size of 2.0 × 2.0 cm. The combined float platform had a radar reflector and solar light per U.S. Coast Guard requirements.

2.3. Steelhead trout

Juvenile rainbow trout were purchased from Sumner Brook Fish Farm in Ossipee, NH. Sumner Brook sourced diploid (all female) trout eggs from Trout Lodge in Sumner, Washington. They were hatched in trays and then placed in 2 m diameter round tanks with flowing freshwater until they were 5 g mean weight. At this size they were transferred to 50 m long, raceways with flowing freshwater and fed twice daily.

Prior to transfer to sea, the fingerlings were fed a 3 mm Bio Oregon transfer diet for 2 weeks. This diet helps transition salmonid smolts from fresh to saltwater environments. It has elevated dietary salts that encourage the development of osmoregulatory ability, while added betaine acts as an osmoprotectant by relieving gastrointestinal stress.

On May 15, 2012, the trout (~100 g) were transported in insulated 1 m^3 containers supplied with oxygen to the Jackson Estuarine Laboratory on Great Bay, NH. Here, they were placed into a 2000-l oval tank and acclimated from freshwater to brackish water (mean salinity of 20). They remained here for 2 weeks to allow their gills to develop chloride cells to adjust to full strength seawater.

In early June, they were transferred to the UNH JGP (mean salinity of 30). They were held in a net pen at the pier and fed 3% body weight/day with a 3 mm Bio Oregon trout diet consisting of 45% protein and 22% lipid and grown to a mean weight of 308.1 g (+/− 81.1) and mean length 28.1 cm (+/− 1.8). On June 20th fish were then transferred to the growout cages (200 / cage) several hundred meters away from the UNH JGP with identical water conditions. After the research, 368 trout (mean weight of 775.5 ± 246 g and mean length of 37.36 ± 2.6 cm) were grown to harvest with local fishers that took turns hand feeding the fish daily with a 6 mm, Bio Trout fish pellet (45% protein, 22% lipid). In November 2012, harvesting commenced and continued once / week until mid-December. At harvest, fish were netted from the sea cages, placed into a saltwater ice bath, bled, gutted, rinsed, and packed on ice in 25 kg totes before delivery to the markets. Fish harvested from both cages were evaluated as a combined biomass. After harvest, the nets were removed and cleaned, and the frames were towed into the JGP area for winter storage. The demonstration site was left to fallow for 5 months until the next growout cycle in the spring of 2013.

To determine the biomass of mussels and kelp required to sequester the nitrogen emitted by steelhead trout into the environment, we used the model developed by Bai et al. (2022) based on the quantity of feed fed. The Bio Oregon fish feed was composed of 7.2% nitrogen. By

Fig. 1. Two steelhead trout cages moored at the mouth of the Piscataqua River, NH used in the integrated multi-trophic aquaculture project.

multiplying this by the total amount of feed fed (515 kg) throughout the study we calculated that ~37.1 kg of nitrogen was to be input into the system. It is estimated that 5% of feed goes uneaten and is lost to the environment in a fish pen (Bai et al., 2022). Of the feed consumed, 50% is excreted through the gills, 10% is lost through feces, and 40% is retained in the trout's tissue. (Bai et al., 2022). The estimated total amount of nitrogen converted to fish biomass was calculated using the following equation:

$$\text{Total N} = (\text{Total N fed x } 95\%) \text{ x } 40\%$$

These numbers were then validated using proximate analysis of the tissues generated by New Jersey Feed Labs in Trenton, NJ, USA.

2.4. *Blue mussels*

New Zealand Catch and Grow Fuzzy Rope was suspended from the floating cage frame to collect mussel spat in the spring of 2011. The fuzzy rope was made from loops of polyester line providing abundant surface area for mussel settlement. Each line was 4 m long and had a 2.0 kg sash weight tied to the end to keep it vertical during strong tidal currents. Mussels typically spawn twice per year in early and late summer in the Gulf of Maine and adhere to bottom substrate and materials in the water column. A total of 55 lines were suspended from the two cages.

On November 15, 2012, the mussels were sampled, and total weight, individual weight, and individual length were measured. A mussel sub sample (tissue and shell) was sent to the New Jersey Feed Labs for proximate analysis. The total nitrogen sequestered by the mussels was calculated by multiplying the total weight of the mussels by the nitrogen content of the mussels.

The research area is closed to shellfish harvest due to its proximity to a sewage treatment facility located 2.4 km upriver (National Shellfish Sanitation Program, 2011). NH regulations mandate that shellfish grown in prohibited waters must be relayed for at least six months in open waters before they can be brought to market. For this reason, the mussels grown in the study were transferred to a UNH mussel farm located at the Isle of Shoals approximately 4.4 km offshore and held there for 6 months prior to harvest and sale.

2.5. *Sugar kelp*

In the late fall of 2012, sorus tissue (gametophytes) was collected from mature kelp and spawned in captivity. With the help of Ocean Approved in Portland, ME (now Atlantic Sea Farms, 20 Pomerleau Street, Biddeford, Maine 04005) and ME Sea Grant, kelp spores were successfully spawned onto twine in captivity utilizing standard techniques (Flavin et al., 2013) and then deployed from cage and around the nets.

Sugar kelp was grown throughout the winter and spring of 2013. Samples (5 kg) of fresh kelp were taken weekly from May 15 through June 25 to a local restaurant in Portsmouth, NH. where it was incorporated in different recipes, and its uses in food evaluated.

2.6. *Environmental monitoring*

As mandated by the EPA, NH Fish & Game (NHFG) and the NH Department of Environmental Services, an environmental monitoring (EM) program was established for the demonstration project. The EM program was designed, vetted through the EPA and carried out by UNH staff. The program included the following:

> Water samples (1 l) were taken 2 m below surface inside the cage, 15 m up current, and 15 m down current from the cage. Sampling occurred in May before the fish were transferred to the sea cages, in August midway through the growout, and again in December after the final harvest. A “Red Sea” test kit was used to measure ammonia, nitrite and nitrate. Other environmental data collected included dissolved oxygen, pH, salinity YSI Pro1030 Waterproof Handheld

pH/Conductivity Meter (YSI Inc., 1700/1725 Brannum Lane Yellow Springs, Ohio 45,387–1107 USA), and current speed and direction (Lowell TCM-1 tilt current meters (Lowell Instruments LLC, 82 Technology Park Drive East Falmouth, MA 02536 USA).

3. Results

3.1. *Steelhead trout*

At harvest, the fish had a survival of 98%, mean weight of 1127.7 ± 96.4 g and mean length of 41.1 ± 0.63 cm. The feed conversion ratio was 1.24 and specific growth rates were 0.32% / day. Total harvest weight for the season was 415.61 kg. The fishermen sold the trout to two local seafood retail markets for $13.20 / kg.

The fish were fed a total of ~515 kg of feed throughout the season, of which ~37.1 kg was nitrogen. Proximate analysis revealed the trout were 18% protein and 3% nitrogen. The 416 kg of steelhead trout therefore assimilated 12 kg of nitrogen, which leaves 25.1 kg of the 37.1 kg nitrogen to be emitted into the environment.

3.2. *Blue mussels*

Results from the proximate analyses indicated a nitrogen content of 1.9% for the mussel tissue and 0.58% for the shell weight totaling ~1.32% for the entire mussel (mussel tissue constituted 57% of total weight). By November, the mussels had a mean weight of 0.18 ± 0.04 g, a mean length of 9.8 ± 3.4 mm, and a density of ~75,500 / m of dropper line. In total, the 55, 4 m dropper lines had a combined weight of 3072 kg. With an N content of 1.32%, the total N sequestered in the shell and tissue was ~40.6 kg (Table 1).

3.3. *Sugar kelp*

Winter growth (January to early April) averaged 0.77 cm per day and kelp blades had a mean length of 0.85 m by mid-April. As water temperatures increased from April to June (7-12 °C), kelp growth accelerated to 3.52 cm / day, and blades averaged 2.5 m in length and had a mean weight of 6.4 kg / m by mid-June. Kelp was harvested end of June, placed into 1 t sacks, and weighed. A total of 638 kg of kelp was harvested.

Proximate analysis indicated that fresh sugar kelp had a nitrogen content of 0.14%. At a total weight of ~638 kg, 0.89 kg of this was N. Combined, mussel and kelp extracted 41.5 kg (40.6 kg + 0.89 kg) of N from the river (Table 1).

Table 1
Nitrogen inputs and outputs from integrated multi-trophic aquaculture.

Nitrogen input from feed			
Date	Total N input (kg)	Total N retained in trout (kg)	Total N emitted into system (kg)
Dec. 2012	37.1	12	25.10
Nitrogen extraction by mussels			
Date	Total line (m)	Total weight (kg)	Total N extracted (kg at 1.32%)
Oct. 2013	220	3072	40.6
Nitrogen extraction by sugar kelp			
Date	Total line (m)	Total weight (kg)	Total N extracted (kg at 0.14%)
Jun. 2013	100	638	0.89
Total N input from trout production			25.1 kg
Total N extraction from mussels and kelp			41.5 kg
Net N extracted from the river			16.4 kg

3.4. *Environmental monitoring*

Results are shown in Table 2. Water temperatures decreased from 17.5 °C in July to 5.3 °C by January. Current speeds during this time ranged from slack to 0.35 m / *sec* and the prevailing direction was NE-SW. The pH of the seawater ranged from 7.6 to 8.0. Dissolved oxygen levels were the lowest in September (87.96% saturation) and highest in January (103.5% saturation). Water samples collected for nitrogen analysis indicated no differences in ammonia, nitrite, or nitrate levels between the sample locations (Table 3).

4. Discussion

This project demonstrated a viable method of culturing steelhead trout, blue mussels, and sugar kelp in sea cages without negatively impacting the surrounding environment. This methodology could be adopted by fishers to create a diversified income from three cultured crops, while overcoming many of the obstacles facing offshore aquaculture.

Steelhead trout exhibited high growth and survival. Survival of 98% achieved in this study is higher than typical trials (89–96%) (Akbulut et al., 2002; Farabi et al., 2020). The observed specific growth rate of 0.32% / day was lower than other studies, which range from 1.02 to 1.44% / day, although sea temperature was considerably lower in this trial than comparable studies (Akbulut et al., 2002; Farabi et al., 2020). The feed conversion ratio of 1.24 in this study was typical of steelhead trout sea cage trials which range from 1.03 to 1.65 (Akbulut et al., 2002, Farabi et al., 2020). However, care must be taken when comparing results from sea trials, as environmental conditions differ greatly between locations. Steelhead trout are grown in ocean pens around the globe and environmental conditions, most notably temperature, dissolved oxygen, salinity, as well as bacterial and parasitic disease levels, are highly variable. Feeding regimes also vary between studies, which greatly impacts growth rates. This study fed just once per day, while research indicates greater growth can be achieved with increased feeding frequency (Türker and Yildirim, 2011). This study was a pilot project to determine feasibility of IMTA in the Gulf of Maine, and its success warrants further investigation using a larger system, with greater biomass and increased feeding, to better evaluate commercial application.

Blue mussels in this study had greater biomass (7.55 kg/m) than in typical growout experiments (0.27–5.2 kg/m) (Guillou et al., 2020). Blue mussels in this study also had far greater densities (75,400 /m) than those typical (2400 /m) (Fréchette et al., 2010). At high densities, mussels often become thinner, having a reduced width: length ratio, although this was not observed in this study (Fréchette et al., 2010). Blue mussels also typically grow more slowly in lower salinity, such as the JGP site (Maar et al., 2015). However, Troell et al. (2003) found that blue mussels grew faster in proximity to a salmon farm than at a reference site outside the influence of the operation. The increased food availability likely explains the high growth observed in this study. The

Table 2
Water quality data collected on 7/26/2012, 9/29/2012 and 1/9/2013 during the demonstration project.

Date	Temp. (°C)	Current direction (°)	Current speed (m/s)	pH	DO (%)	Salinity
7/26/23	16.3	220	0.18	7.97	101.4	29
9/26/23	17.5	45	0.35	7.6	87.9	30.8
1/9/23	5.3	35	0.1	8	103.5	30.1

Table 3
Water sampling for nitrogen content was conducted on 7/26/2012, 9/29/2012 and 1/9/2013 from three locations: 1) inside the cage, 2) 15 m up current and 3) 15 m down current of the fish cages. All values are in mg/L.

		Down current of cage	Inside cage	Up current of cage
7/26/12	NH3	0–0.25	0–0.25	0–0.25
	NO2	0	0	0
	NO3	0.05–0.1	0.05–0.1	0.05–0.1
9/26/12	NH3	0–0.25	0–0.25	0–0.25
	NO2	0	0	0
	NO3	0.05–0.1	0.05–0.1	0.05–0.1
1/9/13	NH3	0–0.25	0–0.25	0–0.25
	NO2	0	0	0
	NO3	0.05–0.1	0.05–0.1	0.05–0.1

proximate analysis results for blue mussel's nitrogen content was slightly higher than those of Rice (1999), who found that the N content of mussel tissue ranged from 1.3 to 1.6% but did not include the shell.

Sugar kelp grew substantially faster (35.2 cm/day) in this study than in other studies (1.1–4.8 cm/day) although total biomass per meter was less (6.4 kg/m compared to 13.3–24.1 kg/m), likely due to lower seeding density (White and Marshall, 2007; Augyte et al., 2017). This study took place near the southern end of its range where temperatures are warmer and near the mouth of the Piscataqua River with nutrient and freshwater inputs, all of which could have led to improved growth rates (White and Marshall, 2007). Perhaps the most important factor in the increased growth rate was the proximity of the kelp to the steelhead trout, which were a consistent source of nutrients and carbon dioxide. Handå et al. (2013) found that sugar kelp grew faster when in proximity to a salmon farm. Similarly, sugar kelp grows more quickly when grown with blue mussels rather than a monoculture (Hargrave et al., 2022). This is caused more by improved irradiance and reduction of epiphytes on kelp blades due to biofiltration processes of blue mussels.

Results from the IMTA of steelhead trout, blue mussels and sugar kelp proved successful in extracting more nitrogen from the Piscataqua River than was added from trout production. This is important as Reid et al. (2007) reported uptake efficiency from IMTA in open water is limited. Mussel and kelp recycle nutrients derived from the fish waste (ammonia and phosphorus). Inorganic nutrients are extracted directly by the kelp from the environment (Neori et al., 2004; Al-Hafedh et al., 2012) while organic nutrients released by the fish feed the mussels (2004; Troell et al., 2003; Mazzola and Sarà, 2001; Reid et al., 2010). Furthermore, mussels are capable of up taking excess particulate fish food, thereby reducing nutrient effluent from the fish farm (). We were able to culture three species in situ and quantify N input and uptake that resulted in ecosystem benefits from aquaculture.

During the IMTA demonstration, NH fishermen were trained “hands on” with the basic skills to culture all three species. Through their efforts, they were able to grow and sell steelhead trout for a high price ($13.20/kg). While participating fishermen recognized the value of the IMTA, commercialization of this system would require an assessment of what fishers would be willing to pay a for production system and how much time it would take daily to maintain the system. Efforts are currently being undertaken to gather this data.

Results of this IMTA project, although still preliminary, could be applied in other New England coastal areas and abroad. An important part of the fishing industries strategy for maintaining their heritage and livelihood is to find alternative ways to diversify their operations. Aquaculture could play an important role in maintaining an active waterfront and fishing heritage. Specific benefits include alternative and economically viable uses for underutilized fishing vessels, employment opportunities for displaced fishers, business and marketing opportunities for suppliers, restaurants, wholesale and retail outlets, and the benefit of locally produced, high quality seafood for local, regional, and national consumers.

CRediT authorship contribution statement

Michael Chambers: Conceptualization, Data curation, Formal analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Michael Coogan:** Writing – review & editing. **Michael Doherty:** Writing – review & editing. **Hunt Howell:** Conceptualization, Data curation, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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