Growing Missouri's Aquaculture Industry: Trends and Outlook

June 2023

MX 462

The following authors contributed to this report:

Ryan Milhollin	State Specialist, Agricultural Business and Policy, MU Extension
Matt Ernst	Independent Writer
Joe Horner	State Specialist, Agricultural Business and Policy, MU Extension
Paul Brown	Eastwood Inc.
Robert Pierce	Associate Extension Professor, Fisheries and Wildlife, MU Extension
David Brune	Agricultural Engineering Professor, University of Missouri
Alice Roach	Senior Research Associate, Division of Applied Social Sciences
Mallory Rahe	State Specialist, Agricultural Business and Policy, MU Extension
Drew Kientzy	Research Program Analyst, University of Missouri

Summary

This report summarizes aquaculture in Missouri, the U.S. and the world. It highlights aquaculture production and consumption, summarizes U.S. and global aquaculture industry trends and offers further detail about channel catfish and rainbow trout — the major fish species grown by Missouri aquaculture producers. Special attention focuses on aquaculture's use of plant-based feeds.

Aquaculture is defined in the National Aquaculture Act of 1980 as "the propagation and rearing of aquatic species in controlled or selected environments." Ponds and lakes are the most common aquaculture environments in the inland U.S. Other production systems include raceways, recirculating systems, non-recirculating systems and aquaponics. In addition to food fish production, aquaculture is important for producing sportfish, ornamental fish and aquatic species for conservation purposes.

Globally, food fish provide an important source of protein and nutrition. Aquaculture can play a key role in meeting growing food demand from an increasing global population while using resources efficiently. Aquaculture systems help to manage and conserve the world's natural fisheries. It also helps supply higher-value seafood products demanded by consumers in developed economies, including the U.S.

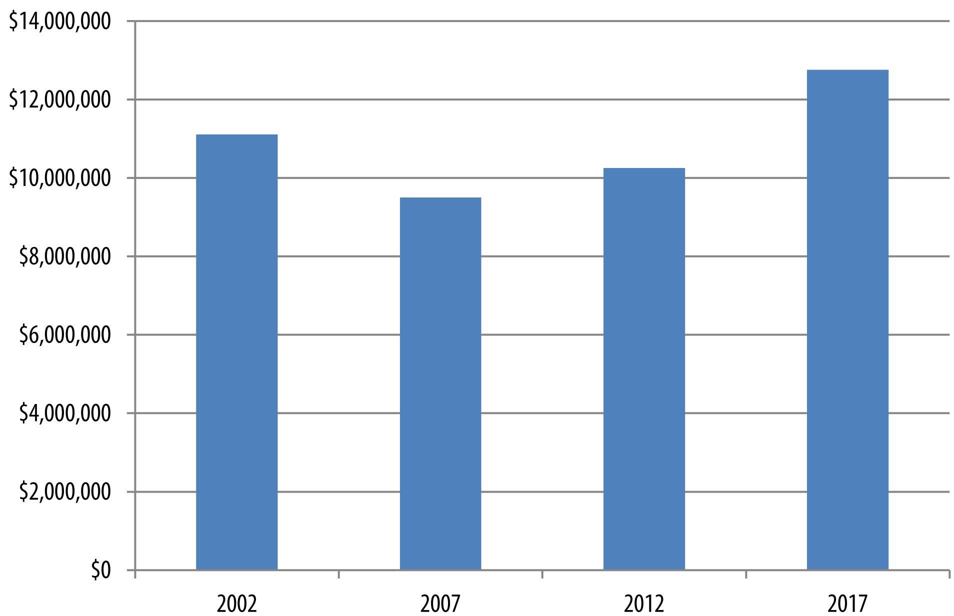
Producer groups have long invested in aquaculture initiatives. Domestic soybean industry investment helped increase U.S. soy protein demand from global aquaculture producers, especially those in Asia. Similar corn industry initiatives resulted in greater aquaculture feed demand for dried distillers grains with solubles (DDGs). From both supply and demand sides, U.S. crop producers have compelling reasons to support U.S. aquaculture. Furthermore, aquaculture enterprises may add viable income streams to existing farms and other businesses in Missouri and the Midwest, especially where it is feasible to include regionally produced grains and oilseeds in aquaculture feed.

1. Aquaculture in Missouri

1.1. Aquaculture Value of Production

In 2017, the market value of agricultural products sold by Missouri producers totaled $12.761 million, according to census data from USDA. This was a slight increase over the market value reported in the three previous agriculture censuses; see Exhibit 1.1.1. Note, when measuring market value, the Census of Agriculture includes aquaculture products distributed for restoration, conservation, enhancement or recreational purposes. USDA's Census of Aquaculture reported Missouri aquaculture sales — from operations with greater than $1,000 of aquaculture products sold — at $7.672 million in 2018.

Exhibit 1.1.1. Missouri Aquaculture Market Value of Production



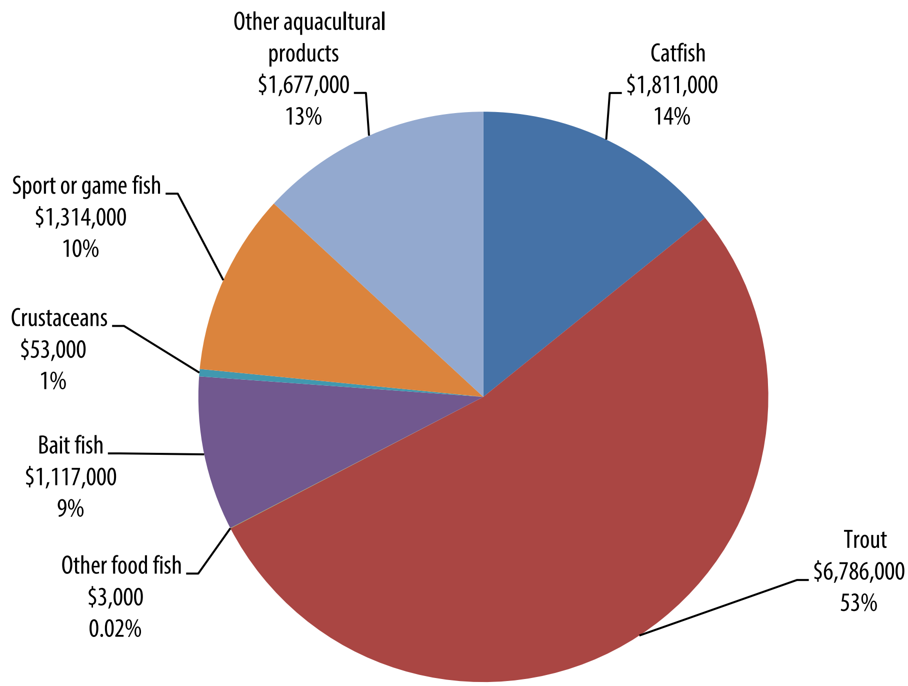
Source: USDA National Agricultural Statistics Service 2019b

1.2. Aquaculture Production Value by Sector

Channel catfish and rainbow trout accounted for two-thirds of Missouri's aquaculture value of production in 2017. Diverse enterprises further contributed to the value of production: sportfish, bait fish, ornamental fish and miscellaneous aquaculture (e.g., freshwater prawns, crayfish, turtles, snails, frogs).

Trout generated just more than half of the market value of Missouri aquaculture production in 2017; see Exhibit 1.2.1. Missouri producers grow not only food-sized trout but also stockers, fingerlings or fry and broodfish. Missouri annually produced more than two million trout for conservation, recreation, enhancement or restoration purposes (USDA NASS 2019a). Trout sold or distributed for conservation and recreation purposes likely make up most of Missouri's trout production value. USDA withholds sales data for different trout categories in Missouri because of a relatively small number of trout producers.

Exhibit 1.2.1. Missouri Aquaculture Market Value of Production, 2017



Source: USDA National Agricultural Statistics Service 2019b

Catfish contributed 14% of Missouri's total aquaculture production value in 2017. Production is common in southern Missouri, where climate and proximity to Gulf Coast allow for marketing and processing catfish and procuring inputs. Missouri also produces stocker and fingerling catfish.

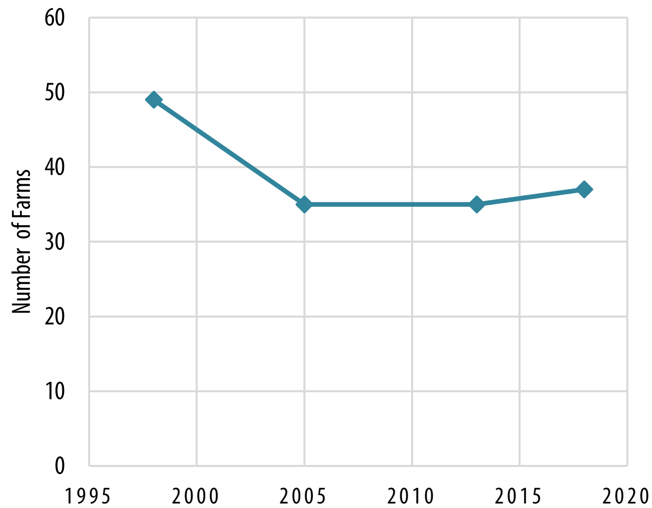
Sportfish, including largemouth bass, and bait fish, such as flathead minnows and golden shiners, combined for about one-fifth of Missouri aquaculture production value in 2017. About 13% of Missouri's aquaculture production value in 2017 was "other aquaculture products" including ornamental fish, turtles, frogs and snails. Other small components of Missouri aquaculture include "other food fish" and "crustaceans" — food species uncommonly produced at substantial scale in the Midwest.

1.3. Aquaculture Producers

The Census of Aquaculture counted 37 Missouri farms that sold aquaculture products in 2018 (Exhibit 1.3.1). For the 2018 Census of Aquaculture, USDA defined an aquaculture farm, including federal or state hatcheries, as a place where $1,000 or more of aquaculture products were produced and sold or produced and distributed for restoration, conservation, enhancement or recreation. Missouri aquaculture farm numbers, especially catfish producer numbers, have declined.

In the past 50 years, the greatest number of Missouri producers selling aquaculture products was reported in the 1987 Census of Agriculture at 134 farms. That included 98 farms with catfish sales — the highest number of Missouri catfish operations recorded from 1974 to 2017.

Exhibit 1.3.1. Missouri Aquaculture Producers



Source: USDA National Agricultural Statistics Service 2019a

Looking at shorter-term operational trends, Missouri operations selling sport fish and bait fish increased from 2013 to 2018. See Exhibit 2.3.2. The percentage of operations with food fish and ornamental fish production decreased. Miscellaneous aquaculture and crustaceans also showed some increase.

Exhibit 2.3.2. Missouri Aquaculture Operations by Product Type Sold, 2013 and 2018

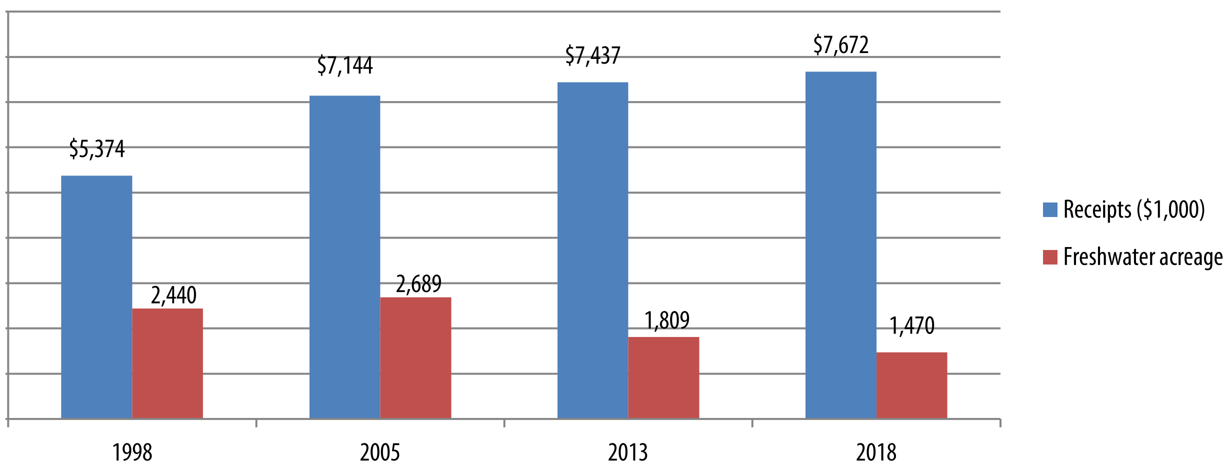
Category	2013	2018	Percent change
Food fish	23	17	-26%
Bait fish	6	11	83%
Sport fish	7	8	14%
Ornamental fish	10	5	-50%
Crustaceans	3	4	33%
Miscellaneous aquaculture	1	4	300%

Source: USDA National Agricultural Statistics Service 2019a

1.4. Missouri Aquaculture Production Area and Practices

Aquaculture production has become increasingly more efficient. Improvements in production technology, fish genetics and nutrition allow aquaculture producers to produce higher volumes of fish from the same — or less — production area. Efficiency of Missouri aquaculture operations parallels efficiency trends nationally. Exhibit 1.4.1 shows total Missouri aquaculture receipts increased modestly from 1998 to 2018, as reported in the Census of Aquaculture. During the same period, freshwater aquaculture acreage declined from about 2,500 acres to 1,500 acres. Three factors contributed to aquaculture receipts in Missouri and elsewhere holding steady while freshwater acreage declined: 1) improved production efficiency, 2) declining area used for lower-value (catfish) production while higher-value (trout) production remained relatively steady and 3) production shifting to species — such as bait fish, sport fish and tilapia — with higher values than commodity catfish.

Exhibit 1.4.1. Missouri Aquaculture Receipts ($1,000) and Freshwater Pond Acreage

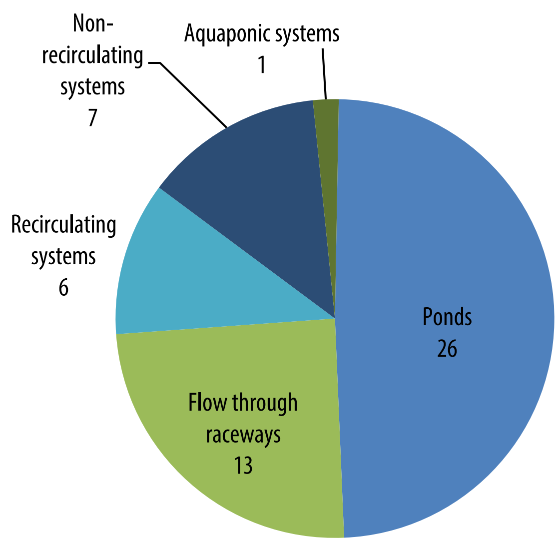


Source: USDA National Agricultural Statistics Service 2019a

Missouri aquaculture producers focus on freshwater pond culture. Ponds were used by 26 of the 37 Missouri respondents to the 2018 Census of Aquaculture (Exhibit 1.4.2). These producers used 943 ponds cumulatively covering 1,385 acres. Each pond averaged 1.5 acres. Total pond area used for aquaculture and average pond size declined since the 2005 Census of Aquaculture.

Flow through raceways were used next most frequently by Missouri aquaculture producers. In 2018, 13 of the 37 respondents to the Census of Aquaculture used raceways. The total number of raceways (276 in total) reached a peak in 2018.

Exhibit 1.4.2. Aquaculture Methods used on Missouri Farms, 2018



Source: USDA National Agricultural Statistics Service 2019a

The 2018 census showed a marked increase in the use of recirculating and non-recirculating aquaculture systems in Missouri relative to 2013. The census reported 87 recirculating tanks, which averaged just more than 2,000 gallons, on six farms. Seven farms reported using non-recirculating systems with 223 total containers. One Missouri farm reported using aquaponics in 2018.

1.5. Comparing Aquaculture in Missouri, Other Midwestern States and Arkansas

Among Midwestern states, Missouri leads in total aquaculture sales. However, neighboring Arkansas has much more extensive aquaculture sales — about nine times the sales reported for Missouri. Exhibit 1.5.1 summarizes the aquaculture operation count and dollar sales for Midwestern states, including Missouri, and Arkansas in 2018. Food fish generated a majority of Missouri's estimated aquaculture sales. Missouri also had much higher sales per operation — 17 food fish operations selling more than $5 million — compared with Ohio's 33 operations that earned about $2.7 million in sales.

Exhibit 1.5.1. Aquaculture Operations and Sales from Select States, 2018

State	All operations with sales		Baitfish operations with sales		Food fish operations with sales		Sportfish operations with sales	
	Number	Total sales ($1,000)	Number	Total sales ($1,000)	Number	Total sales ($1,000)	Number	Total sales ($1,000)
AR	70	67,661	29	22,159	41	29,456	20	13,698
IL	26	4,080	6	(D)	19	(D)	16	2,861
IN	13	3,403	1	(D)	6	(D)	9	(D)
IA	13	3,828	6	124	6	(D)	4	115
KS	4	1,003	3	(D)	4	745	4	(D)
MI	28	3,090	4	267	20	1,843	12	814
MN	19	3,971	9	1,583	12	(D)	7	1,700
MO	26	7,672	11	982	17	5,096	8	570
NE	21	2,761	4	(D)	18	2,343	7	319
OH	59	6,658	14	2,131	33	2,677	29	1,543
SD	3	(D)	2	(D)	2	(D)	1	(D)
WI	59	6,249	7	2,038	45	2,260	16	(D)

Source: USDA National Agricultural Statistics Service 2019a. (D) indicates data withheld due to low operation numbers.

Missouri also differs from other states in the types of food fish produced. According to the 2018 Census of Aquaculture, only seven of the 26 Missouri food fish operations sold species other than trout and catfish. Other species sold, listed in Exhibit 1.5.2, include carp, grass carp and yellow perch. One Missouri operation reported sales of "other" food fish species.

Exhibit 1.5.2. Aquaculture Food Fish Operations by Species from Select States, 2018

State	Total	Hybrid striped bass	Carp	Grass carp	Catfish	Yellow perch	Tilapia	Trout
Number of operations								
AR	41	4	9	9	34	2	2	
IL	19	7	5	5	11			1
IN	13	1	1	1			3	1
IA	13	1	5	5	1	3		1
KS	4		3	3	4		1	1
MI	28				4	8		16
MN	19					8	2	2
MO	17		3	3	8	1		8
NE	21	2	3	3	3	3		14
OH	59	6	13	13	11	15	16	7
SD	3		1	1		1		1
WI	59				2	13	6	26

Source: USDA National Agricultural Statistics Service 2019a. Categories may not add up to totals as some values were withheld for anonymity.

Other states reported more producers of hybrid striped bass, yellow perch and tilapia. Illinois and Ohio had the most hybrid striped bass operations. Yellow perch production was more frequent in states north of Missouri — Michigan, Minnesota and Wisconsin — as well as Ohio. Tilapia production was most frequently reported in Ohio and Wisconsin.

Food fish — other than trout and catfish — produced in nearby states may represent species Missouri fish producers could diversify to grow. In addition, some aquaculture industry observers see expanding inland aquaculture production in the U.S. as beneficial for inland populations. “This is because inland communities consume less seafood and benefit less from the health-giving aspects gained by seafood consumption than coastal communities. Increasing the tie between inland and coast through the finfish aquaculture industry benefits both communities” (Rexroad et al. 2021).

2. Aquaculture in the U.S.

2.1. Volume and Value of U.S. Aquaculture

In 2019, U.S. aquaculture production totaled nearly 658 million pounds (Exhibit 2.1.1), and the U.S. ranked as the 18th largest aquaculture producer in the world. U.S. aquaculture production in 2019 was valued at $1.5 billion — 0.6% of the global value of aquaculture production.

The U.S. has a relatively higher value per pound of aquaculture production compared to the estimated global average value of aquaculture production. Aquaculture is also a high-value segment of the U.S. seafood industry. Although aquaculture accounts for just 7% of U.S. seafood production, the value of U.S. aquaculture production is 24% of the total value of seafood produced in the U.S.

Exhibit 2.1.1. Estimated U.S. Aquaculture Production and Value, 2013 to 2019

	2013	2014	2015	2016	2017	2018	2019
	(Thousand pounds)						
Freshwater							
Catfish	358,380	307,498	317,445	320,174	330,428	350,343	347,990
Trout	44,496	48,456	45,854	48,451	43,750	49,316	33,778
Tilapia	18,428	18,999	18,999	18,999	18,999	14,436	14,436
Striped bass	7,444	8,110	8,111	10,322	9,901	8,688	8,688
Crawfish	106,924	134,168	140,411	149,015	140,270	160,235	162,426
Total freshwater	535,672	517,231	530,820	546,961	543,348	583,018	567,318
Total marine	90,422	90,565	96,539	86,499	87,801	97,210	90,394
Total	**626,094**	**607,796**	**627,359**	**633,460**	**631,149**	**680,229**	**657,712**
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
	($1,000)						
Freshwater							
Catfish	354,337	331,963	347,021	363,075	355,218	341,915	361,910
Trout	71,869	76,206	76,748	79,558	83,151	95,856	66,292
Tilapia	40,049	42,745	42,745	42,745	42,745	37,986	37,986
Striped bass	34,987	31,142	30,831	37,737	36,198	32,800	*32,800
Crawfish	144,347	172,071	199,350	196,695	189,606	210,595	223,630
Total freshwater	645,588	654,128	696,695	719,810	706,918	719,152	722,618
Total marine	401,043	386,081	393,998	418,327	421,922	430,328	430,211
Total miscellaneous	289,181	291,717	302,774	315,944	367,823	374,749	357,282
Total	**1,335,812**	**1,331,926**	**1,393,468**	**1,454,081**	**1,496,663**	**1,517,303**	**1,510,111**

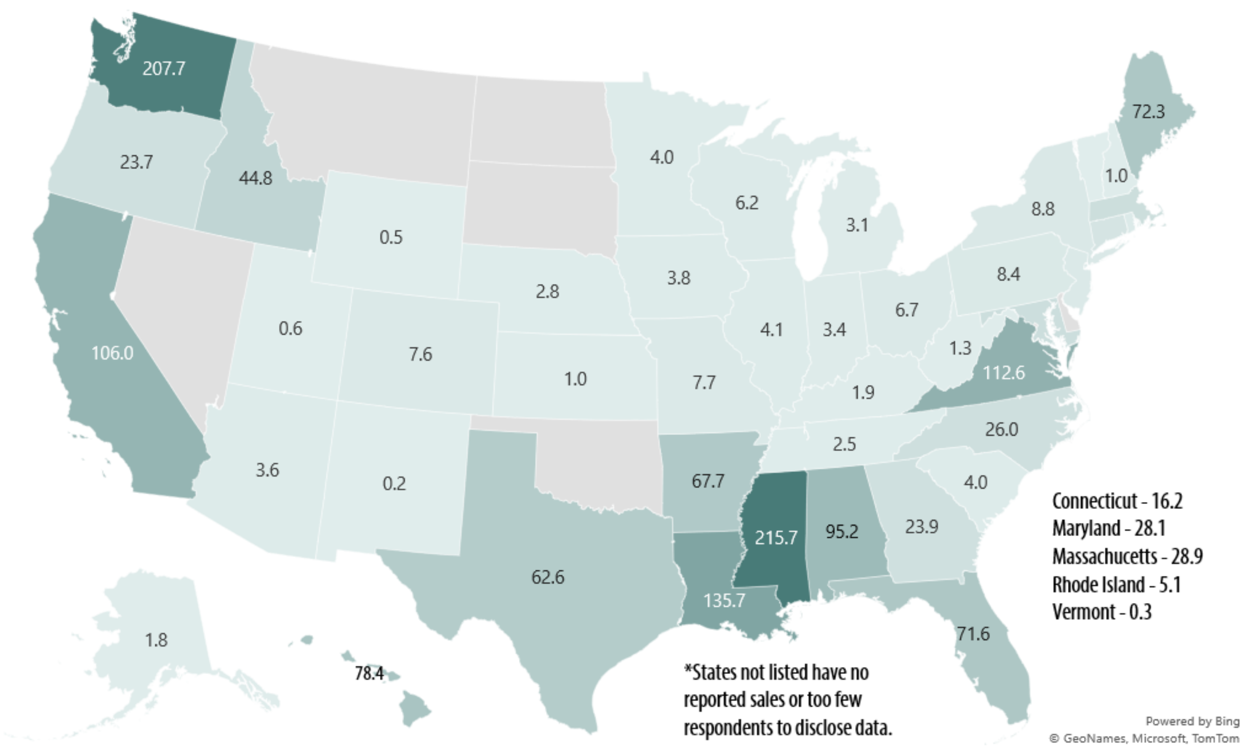
Source: U.S. Department of Commerce 2022. *Estimated

Aquaculture production occurs among a relatively small number of U.S. producers. The 2018 Census of Aquaculture counted 1,071 food fish producers nationwide. By comparison, the 2017 Census of Agriculture reported 304,801 farms producing corn and 303,191 farms producing soybeans (USDA National Agricultural Statistics Service 2019b).

2.2. Major U.S. Aquaculture Production Areas

Mississippi and Washington lead in aquaculture production value. Both produced more than $200 million of aquaculture products in 2018. Mississippi leads in farmed catfish. Mississippi catfish production increased from 3,100 pounds per acre in 2011 to 5,700 pounds per acre in 2019. This increase was mainly because of major improvements in catfish pond management practices and production technology (Posadas 2020). Washington focuses on marine aquaculture — notably salmon and mollusks. Exhibit 2.2.1 highlights production value by state; darker hues indicate higher values. Louisiana, Virginia and California each produced more than $100 million of aquaculture products in 2018.

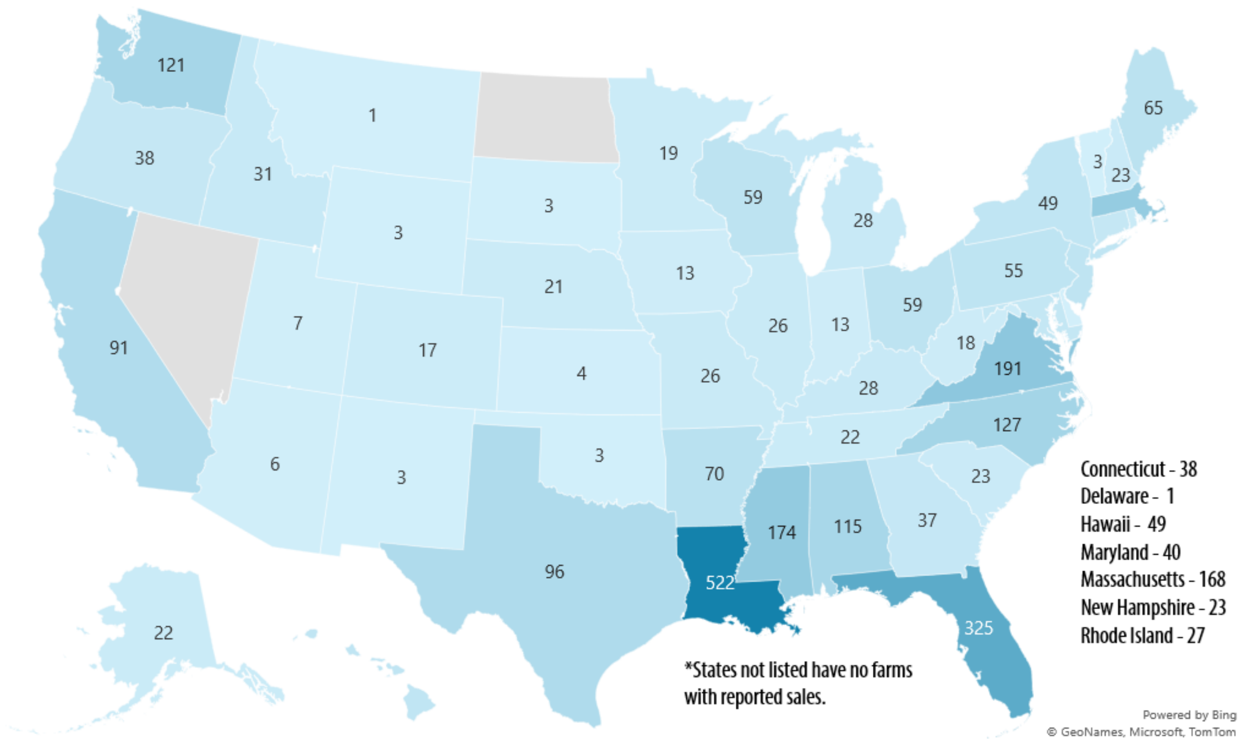
Exhibit 2.2.1. U.S. Aquaculture Production, in Million Dollars, 2018



Source: USDA National Agricultural Statistics Service 2019a

Crawfish farms make Louisiana the U.S. leader in crustacean production. Crawfish production is labor-intensive compared with raising other aquaculture products and requires relatively small production areas per farm. Because of its crawfish production, Louisiana had the most aquaculture farms of any state in 2018 (Exhibit 2.2.2). Florida ranked second in the number of aquaculture producers. Florida led the country in ornamental fish production, which also is associated with smaller production areas per farm.

Exhibit 2.2.2. U.S. Aquaculture Operations with Sales, 2018



Source: USDA National Agricultural Statistics Service 2019a

The U.S. has five aquaculture production regions: Pacific Coast, Gulf Coast/South, Atlantic/Southeast, Atlantic/Middle and Atlantic/North. Farms in each region raise freshwater and marine species, but their production tends to take a regionally distinctive feel.

The value of aquaculture production concentrates in the Gulf Coast/South states. More than half of the country's catfish production is in Mississippi. Alabama is the second largest catfish producer, and Arkansas and Texas also have substantial catfish production. Texas is the leading state for hybrid striped bass. Louisiana aquaculture focuses on crustaceans and mollusks — crawfish and oysters.

Three Pacific Coast states have notable aquaculture industries. Rooted in salmon production, Washington leads aquaculture production in the Pacific states. Idaho produces more farmed trout for food than other states. California is the country's leading tilapia and sturgeon producer, and it is a significant catfish and trout producer.

Aquaculture is diversified along the Atlantic Coast. Maine and Virginia, the leading Atlantic states, primarily focus on saltwater aquaculture (i.e., mollusks). North Carolina has significant catfish and trout production, and it ranks second to Texas in hybrid striped bass production. Farther south, Georgia has significant food fish production of catfish and grass carp. Florida aquaculture producers focus mainly on ornamental fish and saltwater aquaculture, especially shrimp and clams.

States are also differentiated by their average value of production per aquaculture operation. Although Louisiana and Florida have greater aquaculture operation numbers, they have significantly lower production value per farm than Mississippi and Washington. Missouri and Iowa both had higher values of production per aquaculture farm in 2018 than did Louisiana and Florida (Exhibit 2.2.3).

Exhibit 2.2.3. U.S. Aquaculture Production, 2018, Selected States

State ranking	State	Number of farms	Value of production ($1,000)	Production per farm ($1,000)	% of U.S. value
1	Mississippi	174	$215,709	$1,240	14.2
2	Washington	121	$207,685	$1,716	13.7
3	Louisiana	522	$135,712	$260	9.0
4	Virginia	191	$112,640	$590	7.4
5	California	91	$106,021	$1,165	7.0
6	Alabama	115	$95,199	$828	6.3
7	Hawaii	49	$78,429	$1,601	5.2
8	Maine	65	$72,340	$1,113	4.8
9	Florida	325	$71,649	$220	4.7
10	Arkansas	70	$67,661	$967	4.5
11	Texas	96	$62,594	$652	4.1
21	**Missouri**	26	$7,672	$295	0.5
27	Illinois	26	$4,080	$157	0.3
30	Iowa	13	$3,828	$294	0.3
34	Nebraska	21	$2,761	$131	0.2
35	Tennessee	22	$2,544	$116	0.2
36	Kentucky	28	$1,920	$69	0.1

Source: USDA National Agricultural Statistics Service 2019a

2.3. Production Cycles and Supply Chains for Major Freshwater Species

Aquaculture supply chains vary according to species and production systems. Depending on the species and stage of maturity at stocking, many freshwater aquaculture species will require a year or more from stocking until harvest (Exhibit 2.3.1).

Exhibit 2.3.1. Time to Harvest for Major Freshwater Aquaculture Species

Species	Maturity period	Time to harvest
Catfish	Fingerling to harvest	18 months to 2 years
Trout	Stocking to harvest	15 months to 18 months
Tilapia	Fingerling to harvest	6 months (minimum in pond production)
Hybrid striped bass	Fingerling to harvest	15 months to 18 months

Source: Regional aquaculture centers, various reports

The following discussion focuses on catfish and trout production, given these species' importance to Missouri aquaculture. Additionally, hybrid striped bass, yellow perch and tilapia are summarized.

2.3.1. Catfish

Catfish is the major food fish produced by U.S. aquaculture farms. Mississippi is by far the largest catfish producer; it made 60% of U.S. farm-raised catfish sales in 2021. Collectively, Mississippi, Alabama, Arkansas and Texas accounted for 98% of U.S. farm-raised catfish sold for food in 2021 (USDA National Agricultural Statistics Service 2022a). Catfish pond acreage declined in recent years, but production held steady as production efficiency improved.

The catfish industry has an established production chain. Fertilized eggs are produced by four- to six-year-old mature catfish in brood ponds. These eggs are collected and taken to hatcheries where they hatch into "sac fry" with tiny egg yolk sacs. Once sac fry begin to swim, they grow into fingerlings. Nearly 10,000 acres of ponds, mostly in Mississippi and Arkansas, raise broodfish and fingerling catfish. Catfish farms usually acquire fingerlings that measure 4 inches to 6 inches (The Catfish Institute).

Catfish fingerlings take between 18 months and two years to grow into a harvestable 1-pound fish. Harvested with seines, catfish are then transported live to processing plants in tank trucks. According to the Catfish Institute, processing live fish into a fresh or individually quick frozen product takes less than

30 minutes. Fresh and frozen catfish products are widely available for food retailers and foodservice firms through wholesale supply chains.

The U.S. catfish production and processing industry faced several challenges during the pandemic. Wholesale catfish prices decreased 5.2% from January to August 2020 relative to 2015-19 prices. According to an analysis from Mississippi State University, this was most likely because of “the continued decline in the domestic demand by large institutional buyers due to the mandatory closure of their business operations arising from the ongoing public health crisis” (Posadas 2020).

The catfish industry also dealt with increasing feed costs in 2021. However, consumer willingness to pay higher prices for proteins helped support higher producer prices and, in turn, offset higher production costs in 2021. “Prices to producers (from processors) are expected to remain steady or perhaps increase some in 2022. This is because producers will face higher feed costs, and without higher live fish prices, farmers will not be able to meet processors’ demand,” according to Alabama Cooperative Extension.

Exhibit 2.3.1.1. U.S. Catfish and Trout Production, 2020 to 2022

	Water surface area (acres)			Value of production		
	2020	2021	2022	2020	2021	2022
Catfish	60,105	58,300	55,855	$376,948,000	$427,361,000	$447,039,000
Trout				$96,244,000	$98,838,000	$102,920,000

Source: USDA National Agricultural Statistics Service 2022a, b; 2023

2.3.2. Trout

After catfish and salmon, trout is the third leading finfish produced by U.S. aquaculture farms. Rainbow trout is the main species. U.S. aquaculture producers also harvest some brook trout and brown trout.

Trout aquaculture concentrates in northern states — Idaho is the leading producer — but states nationwide have trout farms and hatcheries. These include federal fish hatcheries, such as the hatchery in Neosho, Missouri, that grows rainbow trout for Lake Taneycomo. Also, the Missouri Department of Conservation operates trout hatcheries at each of Missouri’s four trout parks and on Lake Taneycomo.

Access to feed served as an important facilitator of the U.S. trout aquaculture industry’s development. The U.S. Fish and Wildlife Service identified rainbow trout’s nutritional requirements, and development of dry, pelleted trout feeds followed. Pelleted feeds reduced trout production costs by eliminating the need to prepare fresh feeds onsite. This made feeding less labor-intensive (Hinshaw, Fornshell and Kinnunen 2004).

In contrast to the U.S. catfish industry, where fish are raised in clay-lined ponds, today's trout farms usually use concrete raceways. Raceways can increase trout production by 20% to 40% over ponds using the same amount of water (Hinshaw, Fornshell and Kinnunen 2004). Whether raised in raceways, ponds or tanks, most U.S. trout farms use a "flow through" system. Water flows through where trout are raised; the flowing water brings oxygen and removes wastes. Rainbow trout thrive in water temperatures less than 60˚F. The ideal temperature for raising trout from fingerling to harvest stage is 59˚F.

Trout are processed for fresh and frozen sale. Like for catfish, proximity to a processing facility is important for trout production. The value of U.S. trout production in 2022 was $102.92 million — up 4% from 2021 (NASS 2023). As is the case for catfish, U.S. trout aquaculture has room for growth as domestic demand exceeds domestic production. Demand for trout and catfish is stable to growing.

Regulatory requirements are a barrier for expanding trout production, especially for smaller producers unable to spread fixed costs related to regulatory compliance over larger volumes. Environmental regulations — specifically, effluent discharge permitting and monitoring — place the most significant regulatory cost burden on U.S. trout farms (Engle, van Senten and Fornshell 2019). Some aquaculture experts recommend that trout producers known to comply with effluent water quality standards be allowed to reduce effluent testing frequency (Engle, Kumar and van Senten 2020).

2.3.3. Other Species: Hybrid Striped Bass, Yellow Perch and Tilapia

In terms of U.S. finfish aquaculture volume, *hybrid striped bass* rank fourth behind catfish, salmon and trout. Hybrid striped bass are also stocked for sport fishing. In Missouri, they are known by sport fishermen as "wipers" or "whiterock bass" (Missouri Department of Conservation 2022).

The leading hybrid striped bass producer is Texas, where large farms accounted for about half of total U.S. production value in 2018-19 (USDA National Agricultural Statistics Service 2019b). North Carolina ranked second. It and Arkansas dominate hybrid striped bass fingerling production.

The following comments describe economic challenges for hybrid striped bass production: "Input costs are high in hybrid striped bass production. These fish require comparatively high protein diets, and although research is underway to reduce the animal proteins included in these diets, progress has been limited. Hybrid striped bass also require more aeration than species such as catfish and are less tolerant of ammonia. Specific management practices are required to suppress snails in culture ponds, since these are vectors for grub parasites that can reduce both survival and marketability. These high input costs require careful planning for production and marketing to avoid cash flow problems prior to harvest" (Lutz 2022).

Fingerling availability also limits expanding hybrid striped bass aquaculture beyond coastal states. Other challenges involved in producing hybrid striped bass further inland include higher costs for feed and habitat — compared with catfish and trout production — and consumer willingness to pay premiums that translate to profitable production (Mississippi State 2022). A 2015 Purdue University report estimated hybrid striped bass production in cages was potentially profitable in Indiana (Quagrainie 2015).

Hybrid striped bass are harvested at 1.5 pounds to 3 pounds (Andersen et al 2021). Markets prefers bass at heavier weights, which requires harvesting fingerlings some 24 months after stocking. Market demand for heavier hybrid striped bass is creating interest in marine aquaculture production of this species.

Yellow perch have long been a favorite Great Lakes sport fish. These fish have desirable eating characteristics and historically have been the preferred species to prepare for community Friday night fish fry events in the Upper Midwest (Hart, Garling and Malison 2006).

The 2018 Census of Aquaculture reported only $1.1 million in yellow perch aquaculture sales in the U.S. Ohio led with 15 farms and $400,000 in sales. Ohio, Michigan, Minnesota and Wisconsin accounted for two-thirds of the farms producing yellow perch and 81% of production value in 2018. The census reported one Missouri yellow perch producer in 2018.

Despite the limited production, yellow perch do align well with aquaculture systems. They readily train to eat pelleted food. They are also not as affected by crowding and environmental factors as some species, and raising yellow perch in ponds or tanks does not impact fish flavor (Hart, Garling and Malison 2006).

Yellow perch fingerling availability can be a main limiting factor for production. In the past, the aquaculture industry has had limited understanding of procedures for spawning yellow perch and developing fingerlings (Weldon 2019). Knowing yellow perch nutritional requirements — and developing fish feeds to satisfy those requirements – would be necessary to expand yellow perch aquaculture.

In international aquaculture, *tilapia* is very important, but the species has a smaller presence in U.S. aquaculture. California leads in tilapia production by volume. Florida, Ohio, Hawaii and Texas all had more than 10 tilapia farms in 2018. Texas, Florida and Hawaii being included in this list indicates the tropical nature of tilapia, which cannot survive water temperatures below 46°F. Tilapia is often considered for indoor recirculating aquaculture systems and aquaponics.

Tilapia is one of the most consumed fish species in the U.S. However, international aquaculture producers grow, harvest and ship frozen tilapia at much lower price points than most U.S. tilapia aquaculture production systems could feasibly produce these fish. Frozen tilapia from international sources is widely available at U.S. food retailers and wholesalers. Unlike hybrid striped bass or yellow perch, tilapia is a non-native species to Missouri. Non-native species must be raised in a closed system, so they are unable enter other waters. They also require special permission from the Missouri Department of Conservation to be produced commercially (Hicks, Pierce and Brune 2022).

2.4. U.S. Aquaculture Industry Growth

Domestic demand for seafood has outpaced growth in the U.S. fish catch and U.S. aquaculture production. Much of U.S. aquaculture's expansion has occurred in marine aquaculture. During 2013-19 — years for which data are most recently available — U.S. freshwater aquaculture production volume grew at a slower rate than marine aquaculture volume.

The 2010s saw an even greater gap in the rate of increase in U.S. seafood demand and the rate of increase in U.S. aquaculture production. The following are possible reasons:

- Higher fish feed prices hampered aquaculture profitability.
- U.S. producers compete with lower-cost producers of imported fish and seafood.
- Regulatory structures may present difficulty for aquaculture expansion or new producer entry.

U.S. regulations are often highlighted as a barrier for expanding freshwater and marine U.S. aquaculture: "Research using producer surveys and cross-country analysis points toward a link between production volumes and regulations, although there has yet to be a study establishing a robust, causal pathway. Nevertheless, government action in some form appears necessary to make U.S. aquaculture a more significant contributor to domestic and global seafood production. This could range from streamlining state and federal laws to incentivizing seafood cooperatives or offering financial and technical support for producers" (Abaidoo, Melstrom and Malone 2021).

2.5. U.S. Seafood Imports

Fresh and frozen seafood consumption increases would appear to favor domestic aquaculture production. However, U.S. aquaculture must compete with large international aquaculture producers that often have lower costs. Thus, imports have largely supplied the increase in U.S. seafood quantity demanded, and many seafood exporters view the U.S. as a premium target market.

The U.S. imported 6.1 billion pounds of seafood products leading to a $17 billion seafood trade deficit in 2020 (U.S. Department of Commerce 2022). Leading imports have included shrimp, salmon and tuna (Exhibit 2.5.1). Federal agency estimates indicate between 70% and 85% of all seafood consumed in the U.S. is imported (U.S. Department of Commerce 2022).

The U.S. seafood trade deficit continued in 2022 and totaled $24.6 billion. Increased foodservice purchases and rising food prices contributed to the increasing value of U.S. seafood imports. The total value of fishery product imports increased by about 6% in 2022 compared with 2021.

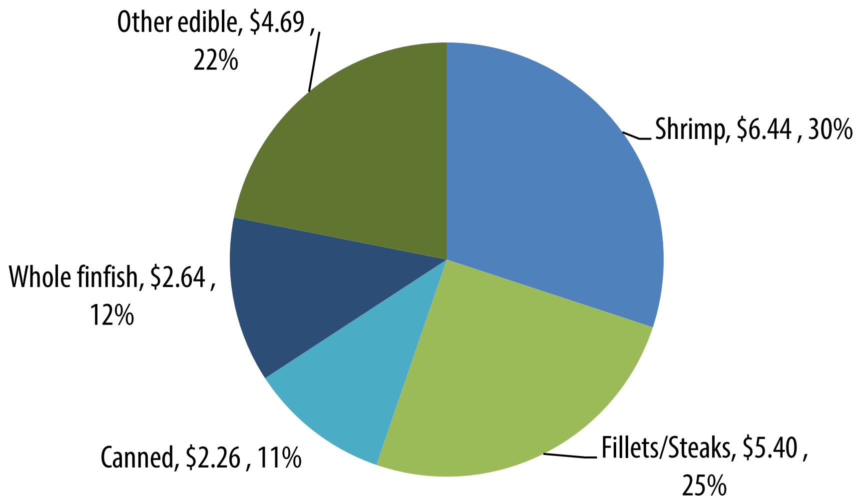
Exhibit 2.5.1. U.S. Fishery Product Imports (Million Dollars)

Species	2017	2018	2019	2020	2021	2022
Shrimps & prawns	6,546	6,238	6,006	6,452	8,018	7,834
All other crustaceans	3,403	3,695	3,830	3,600	6,026	4,837
Salmon, total	3,729	4,096	4,250	4,110	5,250	6,252
All other fish & products	4,755	5,063	4,593	4,240	5,131	6,359
Tuna, total	1,629	1,831	1,918	1,916	1,812	2,415
Molluscs, invertebrates	1,257	1,313	1,157	938	1,512	1,733
Trout, total	136	166	171	164	193	247
Catfish, total	3	1	1	3	4	7
Total imports	**21,458**	**22,405**	**21,926**	**21,423**	**27,946**	**29,682**

Source: USDA Foreign Agricultural Service 2023

Shrimp is the most valuable seafood import category, valued at $6.4 billion in 2020 (Exhibit 2.5.2). Shrimp and fillets/steaks account for more than half of the total import value. Whole finfish imports were about the same value as all canned product imports at 12% and 11%, respectively. Other edible fishery products were 22% of import value in 2020. Alaska Pollock and salmon were the top two types of imported fillets. Tuna was the major canned import.

Exhibit 2.5.2. U.S. Fishery Product Imports by Major Category in 2020 (Billion Dollars)



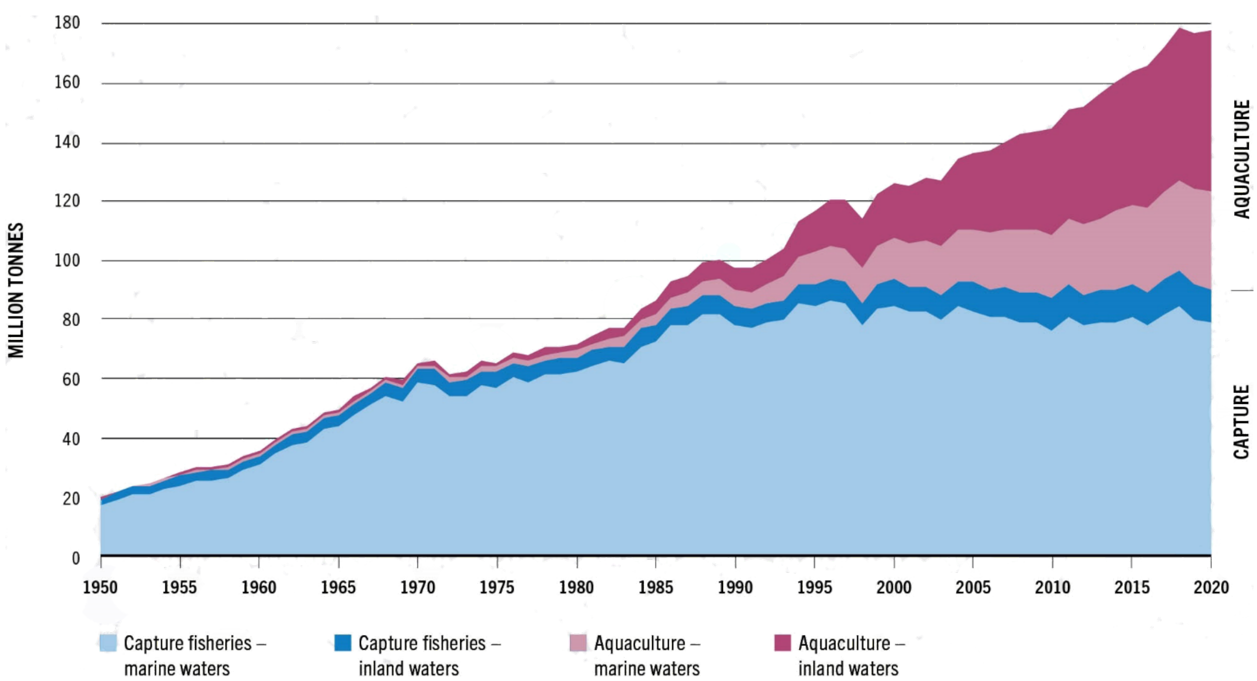
Source: U.S. Department of Commerce 2022

3. Global Aquaculture

3.1. Global Aquaculture Production

Finfish make up two-thirds of global aquaculture food fish production — about 60 million metric tons in 2020 (Food and Agriculture Organization of the United Nations 2022). Aquaculture producers worldwide focus on raising and selling higher value seafood products. In 2018, aquaculture supplied about 52% of seafood for human use and accounted for 62% ($250 billion) of the value of seafood harvested globally (Quagrainie and Shambach 2021). Aquaculture production volume and value of seafood increased from 2018 to 2020 — see Exhibit 3.1.1 — though the rate of increase was slower because of less aggressive growth in major producers and global pandemic impacts in 2020 (Food and Agriculture Organization of the United Nations 2022).

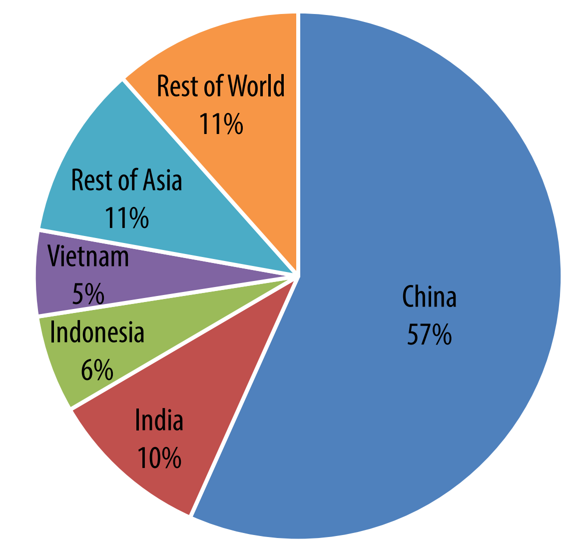
Exhibit 3.1.1. World Capture Fisheries and Aquaculture Production, 1950 to 2020



Source: Food and Agriculture Organization of the United Nations 2022

China, Southeast Asia and India dominate aquaculture production. By far the world's largest producer, China produced more than half of global aquaculture volume and value in 2020. India ranked second, and Indonesia and Vietnam followed (Exhibit 3.1.2). These four countries accounted for about 75% of global aquaculture production volume and 80% of global aquaculture value.

Exhibit 3.1.2. Global Animal Aquaculture (excludes Algae) Production Volume, 2020



Source: Food and Agriculture Organization of the United Nations 2022

3.2. Global Aquaculture Consumption and Demand

Global fish consumption grew at a faster annual rate than the global population from 1961 to 2017. The annual global population growth rate during that time was 1.6%, and the annual increase in fish consumption was 3.1% (Food and Agriculture Organization of the United Nations 2021).

Increased fish consumption is attributed to an increasing fish harvest, including fish harvested from aquaculture. Other factors for increasing global fish consumption include the following:

- Technological developments in processing, cold chain, shipping and distribution.
- Rising incomes worldwide (strongly correlate with increased demand for animal proteins, including fish and fish products).

- Reductions in loss and waste.
- Increased consumer awareness of the health benefits of fish.
- Global population growth increasing the quantity demanded of aquaculture products.
- Consumer willingness to spend on eating out as consumers in developed economies, such as the U.S., consume many aquaculture products when eating away from home.

Increases in quantities demanded and supplied can also heighten marketing risk, including possibilities for saturating markets. For example, the U.S. catfish industry experienced competition from catfish-like imports in the 1990s and early 2000s. Lower-priced imports can challenge U.S. aquaculture, especially during periods of economic recession and higher feed costs (Abaidoo, Melstrom and Malone 2021). The aquaculture industry often supports laws and policies advocating for country-of-origin labeling and other measures that educate buyers about where and how fish were raised and harvested.

3.3. Global Aquaculture Trends

Globally, aquaculture producers report a wide range of production systems, products and markets. This section summarizes ongoing trends among global producers across production systems and regions.

Steady growth is occurring in global aquaculture. Global production of farmed aquatic animals grew by 5.3% annually from 2001 to 2016. Increases in finfish production, especially in China, propelled this growth (Food and Agriculture Organization of the United Nations 2021). The growth rate slowed to 4% in 2017 and 3.2% in 2018. Production in China grew by only 2.2% and 1.7% in 2017 and 2018, respectively. However, aquaculture production volume outside of China increased by 6.7% in 2017 and 5.5% in 2018. Although aquaculture growth has slowed in China, other Asian producers, including Indonesia and Bangladesh, are more rapidly increasing their production.

International trade continues to be central for major aquaculture producers. The U.N. estimates that the global total trade value of fish for human consumption has annually exceeded the trade value of meats raised on land since 2016 (Food and Agriculture Organization of the United Nations 2021).

China and Vietnam are the top two global fish exporters by volume, and aquaculture production is a large portion of their total seafood exports. Aquaculture also figures substantially in fish export volumes from Thailand, Indonesia and India. Production specifically for export has factored into aquaculture industry growth in South and Southeast Asia.

Some countries play important trade roles regionally. Norway has long been an important fish exporter to Europe. Chile has emerged as an important aquaculture exporter to North America and other markets. Both Norway and Chile focus on Atlantic salmon production (Naylor et al. 2021). Canada also has an important maritime aquaculture sector.

It is often noted that the U.S. aquaculture industry has not kept pace with increasing seafood consumption in the U.S. The country's seafood demand has been mainly supplied by imports. However, globally, aquaculture products are primarily used in the country where they are produced. A 2021 article stated, "The growing importance of domestic markets, particularly in Asia, means that over 89% of aquaculture input does not enter into international markets" (Naylor et al. 2021).

Production diversification refers to expanding into different product categories. Data suggest that freshwater (or "inland") aquaculture farms have diversified. Finfish accounted for 97.5% of freshwater aquaculture production in 2000 (Food and Agriculture Organization of the United Nations 2021). By 2018, finfish accounted for 91.5% of freshwater aquaculture production. Growth in Asian freshwater shrimp, crab and crawfish production has driven freshwater aquaculture diversification globally.

Biosecurity is important because disease is a risk to aquaculture industry sustainability and profitability. The biosecurity challenge comes from pathogens, parasites and pests — often termed "PPP" in the industry. Many global advances have been made in identifying and treating PPP in high-value, widely traded aquaculture (Naylor et al. 2021). In many cases, aquaculture biosecurity improvements can be linked with improvements and discoveries made in agricultural science and human medicine. Biosecurity remains a major concern, however, as highlighted in a U.N. report:

"Aquatic animal disease is one of the most serious constraints to the expansion and development of sustainable aquaculture. Globally, a trend in aquaculture is that a previously unreported pathogen that causes a new and unknown disease will emerge, spread rapidly, including across national borders, and cause major production losses approximately every three to five years. Such serious transboundary aquatic animal diseases are most often caused by viruses, but occasionally, a bacterium or a parasite may be the causative agent" (United Nations Food and Agriculture Organization 2021).

4. Aquaculture Feed

4.1. Trends in Aquaculture Feed

Primary ingredients in aquaculture feed rations have historically been fish meal and fish oil. Those feedstuffs offer essential nutrients in a nearly perfect balance for fish growth (Rust et al. 2011). However, both economic and environmental factors have led feed mills to seek alternative ingredients. Plant products have been at the forefront of aquaculture feed development, as summarized in a 2021 *Journal of the World Aquaculture Society* article:

"No other segments of aquaculture have as strong ties to terrestrial agriculture as feeds for the aquaculture production of seafood…. The economic importance of feed from the heartland for the fish farming industry is obvious…." (Rexroad et al. 2021).

Cost is the main economic factor driving aquaculture feed decisions. Feed costs are typically 50% or more of an aquaculture farm's annual variable production costs. Fish-based feeds can be expensive. The global fish meal and oil supply has not increased in more than 30 years, but demand for those ingredients increased significantly as global aquaculture production grew. Increasing demand coupled with stagnant supply pressured prices and caused them to rise greatly in the 2000s. Higher fish feed costs led to more interest in alternative ingredients, and plant-based ingredients were logical options to consider. The salmon and trout industries, for example, used selective breeding strategies and changed feed formulations to allow for increasing a ration's plant protein concentration (Naylor et al. 2021).

Like with livestock and poultry, fish have nutritional requirements that vary by species and development stage. Aquatic species require relatively high dietary crude protein levels. In aquaculture feeds with low dietary protein concentrations, protein content may range from 28% to 32% of the diet, but many feeds contain 38% to 54% protein in the diet. As feed suppliers replaced fish meal with other proteins, essential amino acid deficiencies became apparent. However, feed-grade essential amino acids are readily available and efficacious in aquaculture feeds. The two most common limiting essential amino acids in aquatic animal diets are the same as those for terrestrial livestock: methionine and lysine (Craig et al. 2017).

Harvesting wild fish — the primary supply of fish meal and oil — is intensively regulated and managed. Wild harvest volumes are stable at approximately 90 million metric tonnes; see Exhibit 3.1.1. Fish meal and fish oil costs have risen because of strong demand and stagnant supply. As a result, animal agriculture has moved away from including fish meal and fish oil in feed rations. Aquaculture now accounts for the majority of fish meal and oil use. According to a NOAA/USDA report:

"Although the production of fish meal and fish oil has been relatively constant for decades, supplies of industrial fisheries are limited, and cannot support increased demand from a growing aquaculture industry. Finding alternatives is critical to the long-term sustainable growth of aquaculture in the United States and abroad to meet projected increases in consumer demand for safe, high quality farmed aquatic foods" (Rust et al. 2011).

A related issue is aquaculture feed impact on water quality. Different feedstuffs can have different impacts on water nutrient levels. Ongoing research focuses on helping U.S. aquaculture improve existing rations and develop new feedstuffs to address water quality concerns (Soergel 2021).

4.2. Alternative Protein Ingredients

Optimal crude protein concentrations are high in aquatic animals' diets, and alternative protein feedstuffs have been the focus among suppliers considering alternative feed ingredients. Plant-based feed ingredients are deficient in essential amino acids, particularly the sulfur-containing methionine and cyst(e)ine. Plant-based ingredients represent the largest supply of protein ingredients for animal diets; thus, they tend to be stably priced and not subject to extreme changes. However, plant-based feed ingredients contain chemical compounds that may disrupt digestion and be toxic. These compounds are collectively termed antinutritional factors, and they can limit plant-based protein's incorporation in animal diets (Gatlin et al. 2007). Animal-based feed ingredients — examples include by- or co-products from poultry, swine and bovine processing — are other historically important protein ingredients. As a group, animal-based ingredients do not trigger essential amino acid deficiencies, but disease transmission issues (e.g., bovine spongiform encephalopathy or mad cow disease) have restricted their use in animal feeds. Also, animal by-product meal supplies are much lower than the plant-based ingredient supply.

4.2.1. Soybean Use and Potential by U.S. Aquaculture

In 2018, U.S. aquaculture demanded an estimated 8.6 million bushels of soybeans; the soybean demand likely ranged from 5.5 million bushels to 12.6 million bushels (Engle, Kumar and van Senten 2020). Solvent-extracted, dehulled soybean meal (SBM) — also known as high-protein SBM — has filled almost all of this total soybean demand. Exhibit 4.2.1.1 reports SBM inclusion rates in commercially formulated diets for a variety of aquatic species. Channel catfish feed developers were the first to evolve away from fish meal. For more than 25 years, SBM has been the primary source of crude protein in catfish diets. Tilapia can also readily utilize a diet containing high SBM concentrations — levels similar to catfish diets. Other species that tolerate high concentrations of SBM include hybrid striped bass, crappie, smallmouth bass and sunfish. Substituting SBM for fish meal in diets involves adding feed-grade essential amino acids as well as changing mineral premixes (Brown et al. 1997).

Exhibit 4.2.1.1. Inclusion Rates of Soybean Meal in Commercial Diet Formulations

	Percent of diet from soybeans		
Type of aquatic animal	Mean	Minimum	Maximum
Baitfish	35%	22%	51%
Carp	0%	0%	0%
Catfish	35%	22%	51%
Crappie	25%	20%	48%
Hybrid striped bass	31%	20%	40%
Largemouth bass	25%	20%	48%
Ornamental fish	3%	2%	5%
Prawns	13%	10%	28%
Smallmouth bass	25%	20%	48%
Sunfish	40%	25%	48%
Tilapia	35%	22%	51%
Trout	15%	10%	20%
Walleye	15%	10%	23%
Other food fish	15%	10%	20%
Other sportfish	15%	10%	23%

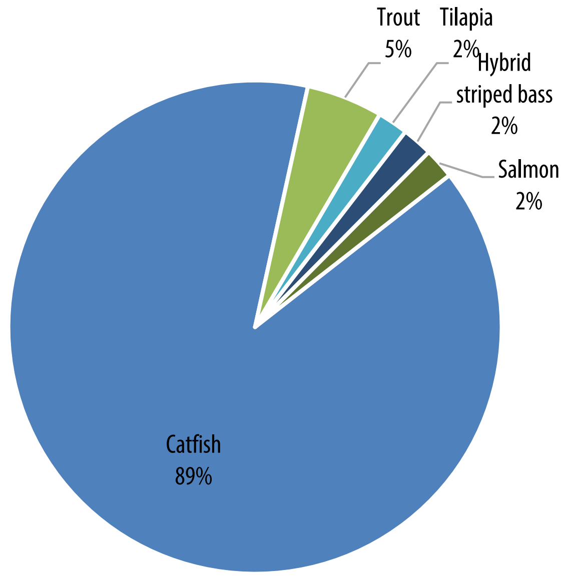
Source: Engle, Kumar and van Senten 2020

Catfish consume 89% of SBM demanded by U.S. aquaculture (Exhibit 4.2.1.2). Trout rank second and account for 5% of U.S. aquaculture's SBM demand. However, feed suppliers have room to include more soy in trout diets. The 2020 report stated, "With increased inclusion rates of soybean meal that have been reported to be nutritionally feasible for trout production, soybean demand from U.S. trout production would increase by 50%, or 141,612 bushels above current maximum recommended inclusion levels."

If the U.S. replaced trout imports with domestic production, then soy protein would have additional market potential in trout diets. This impact could nearly double the trout industry's soybean demand from about 200,000 bushels to 400,000 bushels.

U.S. tilapia producers have historically focused on producing live fish for home preparation. However, efforts to expand large-scale U.S. tilapia production — including fish raised for processing and freezing — could significantly increase the amount of SBM sourced for tilapia feeds (Engle, Kumar and van Senten 2020).

Exhibit 4.2.1.2. Percent of Soybean Demand by U.S. Aquaculture Segment



Source: Engle, Kumar and van Senten 2020

Soy protein concentrates (SPC) have also been evaluated in aquaculture feeds. They are efficacious and have higher crude protein concentrations (~64%) than SBM. Therefore, they lead to fewer essential amino acid deficiencies in fish and shellfish. However, SPC adds cost, which commonly limits SPC use to less than 5% to 10% of the diet. SPC is most often incorporated into diets containing high crude protein (40% and higher) levels. Soy protein isolates contain approximately 80% crude protein, but they are prohibitively priced for animal diets.

4.2.2. Distillers Products Use and Potential by U.S. Aquaculture

Use of distillers products, including grain distiller's dried yeast, distiller's dried grains with solubles (DDGS) and high protein DDGS, is expanding in aquaculture diets. Researchers have looked at distiller's dried yeast for inclusion in rainbow trout and salmon diets (Sealey 2022). Since the 1940s, studies have evaluated DDGS use in fish diets and suggested that high-protein DDGS may replace fish proteins in aquaculture feeds (Sealey 2022). DDGS not only contain higher protein concentrations but also display higher nutrient digestibility.

Corn DDGS combined with soybean meal can replace fish meal and other ingredients, particularly for fish species, such as tilapia and catfish, with a high-fiber diet (U.S. Grains Council 2018). Including

DDGS in diets of other important aquaculture species, such as rainbow trout and hybrid striped bass, requires adding feed-grade amino acids such as lysine and methionine (Sandor et al. 2021). Still, reduced-oil corn DDGS have the potential to be a large part of aquaculture diets. According to the most recent DDGS User Handbook: “Research evaluating optimal diet inclusion rates of DDGS in diets for various aquaculture species is limited, but recent studies have shown there are significant opportunities to substantially reduce diet costs while achieving satisfactory growth performance, survival and flesh quality” (U.S. Grains Council 2018).

Exhibit 4.2.2.1 reports the recommended maximum DDGS inclusion rates in diets for selected aquaculture species. Ragab et al. (2023) also recently summarized the use of DDG in aquaculture feeds.

Exhibit 4.2.2.1. Recommended Maximum DDGs Inclusion Rates for Various Aquaculture Species

Species	Maximum dietary DDGS inclusion rate %
Channel catfish	30 to 40 with supplemental synthetic amino acids
Rainbow trout	50
Tilapia	50 with supplemental synthetic amino acids
Freshwater prawns	40
Red claw crayfish	30
Hybrid striped bass	10

Source: U.S. Grains Council 2018

4.2.3. Additional Plant-Based Ingredients

Protein ingredients are the primary concern when formulating aquatic animal diets, and soy products along with DDGs and animal by-product meals are logical ingredients to consider in the Midwest, which has adequate supplies for large-scale diet manufacturing. However, grain products also play a critical role, and two commodity grain crops are grown in large supplies in the Midwest. Corn and wheat products are commonly added in diets, but they play a lesser role in meeting aquaculture species’ nutritional needs compared with terrestrial animals’ needs. Cereals and grains contain low concentrations of crude protein and high concentrations of carbohydrates. Carbohydrates are not as well-utilized as an energy source by aquatic animals. However, they are necessary for diet manufacturing. Almost all aquatic animal diets are extruded to make them more stable in water and not subject to degrading quickly. Further, most extruded diets float on the water’s surface and force animals to the surface to feed. This provides an important management benefit as fish farmers can evaluate feeding behavior and not overfeed. Corn grain, wheat midds and whole wheat are the most common grains used in aquaculture feeds. Carbohydrate concentrations in extruded aquatic feeds commonly range from 15% to 20%, and grains are incorporated to provide that concentration. Processed corn and wheat coproducts are increasingly used in aquaculture feeds but at low concentrations.

Two commonly available processed corn coproducts are corn gluten feed (CGF) and corn gluten meal (CGM). CGF has a lower crude protein concentration (~21%) than CGM (~63%) and is not commonly added to aquaculture feeds. CGM has been increasingly used in aquaculture feeds but at less than 10% of the diet. High concentrations of commodity CGM also contain high concentrations of xanthophylls, a pigment retained in fish muscle. This feature calls for restricting CGM use in aquaculture feeds. White CGM has potential as an ingredient, but its supply and price preclude most feed mills from using it. Wheat gluten meal contains approximately 80% crude protein and has potential in aquaculture feeds, but it is not commonly used — largely due to price.

Other plant-based ingredients, including canola meal, lupin meal, pea proteins and cottonseed meal (CSM), have been evaluated extensively in aquaculture feeds. However, they are available largely outside of the Midwest and would have to be shipped to local feed mills. CSM became a common ingredient in channel catfish diets. It has potential as an ingredient used in Missouri as the supply is relatively close.

4.2.4. Animal By-Product Meals and Potential Use in Aquaculture Feeds

The most common animal by-product meals used in aquaculture feeds include meat and bone meal (MBM), blood meal (BLM), poultry by-product meal (PBPM) and feather meal (FM). Although animal by-product meals are less available than common plant-based ingredients, they tend to be competitively priced. More importantly, animal by-product meals complement plant-based ingredients deficient in essential amino acids. Feed suppliers commonly blend plant-based and animal by-product meals to develop fish meal-free aquaculture feeds. In addition to disease transmission issues, the ongoing challenge with animal by-product meals is the potential for nutritional inconsistency due to inconsistency in input streams. This concern has generally limited animal by-product meal use into some feed mills. However, the rendering industry has secured more stable input streams, and by-product meal use tends to increase as fish meal prices continue rising.

MBM, largely from porcine sources, has been successfully substituted into diets for hybrid catfish (blue x channel), Pacific whiteleg shrimp, gilthead seabream and hybrid striped bass. Most quantitative evaluations of MBM recommend concentrations up to 40% to 50% of the diet. Animal by-product meals do not contain antinutritional factors found in plant-based ingredients and should be considered safe and efficacious for aquaculture feeds.

BLM contains approximately 90% crude protein and high concentrations of essential amino acids. However, it is relatively expensive and tends to display low nutrient digestibility. Although BLM is common in many aquaculture feeds, levels of incorporation are commonly 5% or less because of expense.

The poultry by-product meals have become common in aquaculture feeds. FM was the initial interest as it has high sulfur amino acid concentrations. However, FM digestibility is lower than many other ingredients' digestibility. FM has become less common, but PBPM has become more commonly used. Input streams into poultry processing tend to be consistent, and pricing has been competitive.

Relatively few quantitative evaluations have focused on poultry products in aquaculture, but these ingredients have become common in diets. Like MBM products, poultry products do not contain antinutritional factors, and they are generally safe and efficacious. Disease issues, thus far, are less of a concern when using poultry products compared with ovine or bovine products.

4.2.5. Novel Protein Ingredients

Numerous new ingredients have entered the feed production markets, and many focus on supplying crude protein in aquaculture feeds. The continued growth of global aquaculture industries and the pressure those industries place on ingredient use has stimulated new ingredient industry development. Novel proteins include insect meals, algae meals and bacterial meals. Insect and algal meals have the most potential in the short-term as they have increasing supply. New insect meal production facilities have been developed in Canada, and one is under construction in Illinois — a joint venture between ADM and InnovaFeed. The Illinois facility has targeted output of 60,000 metric tons of meal per year. Laboratory testing of insect meals, most commonly black soldier fly larvae (BSFL), has demonstrated efficacy and safety of these products in a wide range of aquaculture species. In a recent review of insect meal use in aquaculture feeds, Alfiko et al. (2022) indicated no significant limitations to use insect meals in aquaculture feeds. Many evaluations found BSFL could replace all fish meal in diets. BSFL meal pricing from the Decatur, Illinois, facility has not been announced.

The supply of algal meals is increasing, but it's small compared with commodity ingredient supplies. As with other plant-based ingredients, algal meals have had limited incorporation into aquaculture feeds.

Some studies have identified growth decreases with as little as 10% algal meal in the diet. Thousands of algae species are available, and their nutritional concentrations vary. As algal production focuses on desired species and supply increases, algal meals may become a more common ingredient in aquaculture feeds. In the short term, the primary product from algae culture is the oil, which contains high concentrations of long-chain n-3 polyunsaturated fatty acids.

4.3. Alternative Lipid Sources

The supply of fish oil, like fish meal supplies, has not increased in more than 30 years, and it is unlikely to increase in the future. Global aquaculture production growth places the same pressures on fish oil as on meal, and alternative lipid sources have been another focal point of aquatic animal nutrition research. However, lipids in feeds are easier to substitute than proteins. Lipids are the primary source of dietary energy for aquatic animals, and they all are effectively utilized. Lipids also supply essential fatty acids, and aquatic animals retain n-3 fatty acids they consume in diets. The n-3 fatty acids found in seafood contributes to the argument for consuming more fish and shellfish.

Choosing a lipid for aquatic feeds becomes very complex, and the literature summarizes the potential to use soy oil and other plant-based lipids (Brown and Hart, 2010). However, from a practical perspective, dietary formulations have been using a 1:1 mixture of fish oil and plant-based lipids, including soy, corn and canola. Animal by-product lipid sources have also been used with success. When choosing a lipid, pricing and availability into feed mills become important considerations as most lipids are efficacious.

4.4. Aquaculture Feeds in Missouri

Aquaculture feeds are some of the more complex diets to manufacture because of the equipment needed. Aquaculture feeds are extruded, and the industry will be reluctant to accept pelleted diets. Thus, feed mills need an extruder. Single-barrel extruders are effective in manufacturing aquaculture feeds, but they produce a limited range of products. Twin-barrel extruders are preferred as manufacturing conditions can be modified to produce a sinking extruded feed, which has become the preferred form for several aquaculture species — chiefly shrimp — that feed slowly and on the bottom of ponds or tanks. Diets for many carnivorous species, such as trout or salmon, contain high levels of dietary fat (16% to 30% of the diet) — concentrations that exceed the ability to extrude efficiently. In those situations, fat must be added post-extrusion or “top dressed,” which would be an additional manufacturing issue.

In addition to an extruder, mills will need bulk storage bins, grinders and equipment to feed the ground mix into the extruder. Bagging capabilities are common in aquaculture feed mills, and bulk bags are beneficial for customers feeding many fish and shrimp. Most feeds in the Midwest are sold in 40- to 50-lb. bags stacked on a pallet and wrapped in visqueen plastic sheeting. Thus, facilities must bag feed, stack bags on pallets, wrap pallets and load full pallets onto trucks to efficiently transport feed to buyers.

Given that extruders produce feed in 5- to 20-ton batches, storage capacity at mills is another consideration. Aquaculture feeds should be stored in cool, dry locations out of direct sunlight, and they should be fed within six months of manufacturing.

Missouri has significant manufacturing capacity for companion animal (i.e., dog, cat) feeds that are commonly extruded. Thus, these facilities have potential to add an aquaculture feed product line.

4.4.1. Atypical Ingredients Needed

Vitamin and mineral premixes formulated for aquatic animals will be atypical ingredients needed by feed mills that make aquaculture feeds. Mills commonly purchased bagged premixes and add them during the mixing phase of manufacturing. The one almost unique ingredient needed for aquaculture feeds is vitamin C. All aquatic animals require vitamin C, and it is commonly added separate from the vitamin premix. Rovimix Stay-C 35 from DSM has become the preferred source of vitamin C as it can be added to the mix pre-extrusion. Stay-C is a polyphosphated form of the vitamin that does not degrade significantly during extrusion. Lecithin (phosphatidylcholine) is another ingredient added to aquatic animal feeds. Mills may not routinely have lecithin available. The most common source of lecithin is soy.

4.4.2. Expertise Needed

Trained nutritionists can formulate diets for aquaculture species using review articles and the National Academy of Sciences National Research Council publication "Nutrient Requirements of Fish and Shrimp" (NRC 2011). However, the volume of aquaculture nutritional data published every year verges on massive. Keeping up with contemporary approaches and data is challenging. Employing aquatic animal nutritionists would be an important initial step in developing an aquaculture feed line.

Hundreds of dietary formulations for fish and shrimp have been published, but an almost unique interaction should occur between any consultant and feed mill. Although consultants can provide formulae that meet target species' nutritional needs, they do not always have access to information about ingredients available, costs, short- or long-term ingredient purchasing philosophies, business expectations (i.e., margins) and emergence of new ingredient availability.

Ingredients in aquaculture feeds are not commonly substituted as prices change on global markets (i.e., aquaculture feeds are not least costed). Once formulations are established, they tend to remain the same for extended time periods. Aquatic animals can display reluctance to accept new formulations or formulations in which an ingredient has been substituted. Interaction between consultants and customers can be invaluable, particularly when a mill is developing a new product line. The supply chain will have initial reluctance to accept diets from a new entrant. Further, aquaculture farmers have specific expectations for their feeds (e.g., ingredients, macronutrient concentrations) that mills new to manufacturing aquaculture feeds must satisfy.

5. Conclusion

Missouri aquaculture firms produce fish and other aquatic species for food, recreation and conservation purposes. Catfish and trout are the major food species produced in Missouri. The major recreation and conservation species are trout and various sport fish. The value of Missouri aquaculture production has remained steady to slightly increased in recent years. According to data from the 2018 Census of Aquaculture, Missouri ranked 21st among U.S. states in the value of aquaculture production, and it was the leader among states in the north central region.

U.S. aquaculture production has not kept up with domestic growth in seafood product demand — even when seafood supply and demand were disrupted during recent recession and pandemic periods. Several factors have been cited for the lack of U.S. aquaculture expansion. North American producers compete with international aquaculture producers that have lower production costs, particularly labor, and can ship frozen fish products at lower price points than domestic producers. Labor available to process seafood is also a limiting factor. Regulations for aquaculture production have also been cited as a barrier to entry, particularly for firms interested in expanding maritime (saltwater) aquaculture production.

Demand for seafood products is expected to continue increasing. More than half of seafood in the U.S. market is consumed away from home, so institutional foodservice and restaurants heavily influence the domestic seafood market. Competitive wholesale pricing is central to capturing U.S. foodservice markets. Population and dietary trends indicate U.S. seafood consumption will remain at current levels or perhaps increase as some consumers perceive fish consumption to improve their overall health. Offering seafood that is easy to prepare at home — for example, frozen fillets and easy-to-cook products — is viewed as central to increasing the reach of U.S. aquaculture products among domestic consumers.

Trends in U.S. aquaculture production are similar to those in global aquaculture. They include the impact of industry growth and international trade. Product diversification, including offering products that are more convenient for at-home consumption, is also a global aquaculture trend. Biosecurity — managing pathogens, parasites and pests — has extreme importance for aquaculture production. Global aquaculture producers are also expected to continue using more plant-based feeds. Soybeans are prominently used in fish rations, and soybean usage in U.S. aquaculture has increased. Aquaculture has also increased feed usage of distillers products, including corn DDGS.

References

Abaidoo, Eric, Max Melstrom and Trey Malone. 2021. "The Growth of Imports in U.S. Seafood Markets." *Choices* Vol. 36 Quarter 4.

Alfiko, Yuzer et al. 2022. "Insects as a Feed Ingredient for Fish Culture: Status and Trends". Aquac. Fish. 7:166-178. doi.org/10.1016/j.aaf.2021.10.004.

Andersen, Linnea K., et al. 2021. "The Status of Striped Bass, Morone Saxatilis, as a Commercially Ready Species for U.S. Marine Aquaculture." J World Aquac Soc. 2021;52:710–730. Accessed at onlinelibrary.wiley.com/doi/pdf/10.1111/jwas.12812.

Brown, P.B., R. Twibell, Y. Jonker and K.A. Wilson. 1997. "Evaluation of Three Soybean Products in Diets Fed to Juvenile Hybrid Striped Bass Morone Saxatilis x M. Chrysops". J World Aquac Soc 28:215-223.

Brown, P.B. and S.D. Hart. 2010. "Soybean Oil and Other N-6-Rich Lipid Sources". Pages 133-160 in: G. Turchini, W. Ng and D. Tocher, editors. Fish Oil Replacement and Alternative Lipid Sources in Aquaculture Feeds. CRC Press, Taylor and Francis Group, New York, NY.

Craig, Steven, Louis Helfrich, David D. Kuhn and Michael H. Schwarz. 2017. "Understanding Fish Nutrition, Feeds, and Feeding." Virginia Cooperative Extension Publication 420-256.

Engle, Carole R., Ganesh Kumar and Jonathan van Senten. 2020. "Potential Economic Value of Growth of U.S. Aquaculture to U.S. Soybean Farmers." Soy Aquaculture Alliance.

Engle, Carole R., Jonathan van Senten and Gary Fornshell. 2019. "Regulatory Costs on U.S. Salmonid Farms." J World Aquacult Soc. 2019;50:522–549. Accessed at onlinelibrary.wiley.com/doi/epdf/10.1111/jwas.12604.

Food and Agriculture Organization of the United Nations. 2022. *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*. Accessed at doi.org/10.4060/cc0461en.

Food and Agriculture Organization of the United Nations. 2021. *The State of World Fisheries and Aquaculture 2020*. Accessed at fao.org/documents/card/en/c/ca9229en/.

Gatlin, D.M., III, F.T. Barrows, P. Brown, K. Dabrowski, T.G. Gaylord, R.W. Hardy, E. Herman, G. Hu, A. Krogdahl, R. Nelson, K. Overturf, M. Rust, W. Sealey, D. Skonberg, E.J. Souza, D. Stone, R. Wilson and E. Wurtele. 2007. "Expanding the Utilization of Sustainable Plant Products in Aquafeeds: A Review". Aquac. Res.38:551-579.

Hart, Steven D., Donald L. Garling and Jeffrey A. Malison (eds.). 2006. *Yellow Perch (*Perca flavescens) *Culture Guide*. North Central Regional Aquaculture Center. NCRAC Series #103. Accessed at freshwater-aquaculture.extension.org/wp-content/uploads/2019/08/ Yellow_Perch_Culture_Guide.pdf.

Hicks, Charles E., Robert A. Pierce II and David Brune. 2022 (Revised). "Converting Unused Agriculture Facilities for Aquaculture Use: Swine Barn Conversion for Fish Culture." University of Missouri Extension Publication G9472.

Hinshaw, Jeffrey M., Gary Fornshell and Ron Kinnunen. 2004. "A Profile of the Aquaculture of Trout in the United States." Accessed at freshwater-aquaculture.extension.org/wp-content/uploads/2019/08/ Trout_Profile.pdf.

Lutz, C. Greg. 2022. "Hybrid Striped Bass." Louisiana State University Agricultural Center. Accessed at agmrc.org/commodities-products/aquaculture/aquaculture-fin-fish-species/hybrid-striped-bass.

Mississippi State University Extension. 2022. "Hybrid Striped Bass." Accessed at extension.msstate.edu/catfish/other-aquaculture-species/hybrid-striped-bass.

Missouri Department of Conservation. 2022. "Hybrid Striped Bass." Accessed at mdc.mo.gov/discover-nature/field-guide/hybrid-striped-bass-wiper-whiterock-bass.

NRC (National Research Council). 2011. "Nutrient Requirements of Fish and Shrimp". National Academy of Sciences, Washington, DC.

Posadas, Benedict C. 2020. "U.S. Catfish Production, Farm-gate and Wholesale Prices, and Imports." Mississippi MarketMaker Newsletter, Vol. 10, No. 8. Accessed at extension.msstate.edu/newsletters/mississippi-marketmaker.

Quagrainie, Kwamena K. and Amy M. Shambach. 2021. "Aquaculture Markets in the Twenty-First Century." *Choices* Vol. 36 Quarter 4.

Quagrainie, Kwamena. 2015. "Profitability of Hybrid Striped Bass Cage Aquaculture in the Midwest." Purdue Extension. Accessed at iiseagrant.org/wp-content/uploads/2019/11/EC-798-W.pdf.

Naylor, Rosamond L. et al. 2021. "A 20-year Retrospective Review of Global Aquaculture." *Nature* Vol 591 25 March 2021. Accessed at doi.org/10.1038/s41586-021-03308-6.

Ragab, Sherine, et al. 2023. "Evaluation of Distiller's Dried Grains with Solubles in Aquafeeds: a Review". Ann Anim. Sci. doi: 10.2478/aoas-2023-0051.

Rexroad, Caird at al. 2021. "Opportunities for U.S. Marine Finfish Aquaculture." *J World Aquac. Soc.* 2021; 52:501-508.

Rust, Michael B. et al. 2011. "The Future of Aquafeeds." NOAA Technical Memorandum NMFS F/SPO-124. NOAA/USDA Alternative Feeds Initiative, December 2011. Accessed at spo.nmfs.noaa.gov/sites/default/files/tm124.pdf.

Sandor, Zsuzsanna J. et al. "Potential of Corn Distiller's Dried Grains with Solubles (DDGS) in the Diets of European Catfish (*Siluris glanis*)." Aquaculture Reports Vol. 20 July 2021. Accessed at doi.org/10.1016/j.aqrep.2021.100653.

Sealey, Wendy M. 2022. "Expanding Use of Distillers Products in Aquaculture Diets." Presentation at 2022 Distillers Grains Symposium. Accessed at distillersgrains.org/wp-content/uploads/2022/05/5-Sealey-DDGS-May-2022-Aquaculture-Diets.pdf.

Smith, Matthew A. and C. Greg Lutz. 2022. "Introduction to Aquaculture in the North Central Region." North Central Regional Aquaculture Center. Accessed at store.extension.iastate.edu/FileDownload.ashx?FileID=4930.

Soergel, Allison Arteaga. "New Research on Aquaculture Feed will Test Alternative Ingredients to Help Minimize Water Pollution." UC Santa Cruz, July 2, 2021. Accessed at news.ucsc.edu/2021/07/low-pollution-fish-feed.html.

The Catfish Institute. "Farming and Processing." Accessed at uscatfish.com/farming-and-processing.

USDA Foreign Agricultural Service. 2022. Global Agricultural Trade System Database, February 16, 2023. Accessed at apps.fas.usda.gov/gats/default.aspx.

USDA National Agricultural Statistics Service. 2019a. 2018 Census of Aquaculture. United States Department of Agriculture. Accessed at nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Aquaculture/index.php.

USDA National Agricultural Statistics Service. 2019b. Census of Agriculture. United States Department of Agriculture. Accessed at nass.usda.gov/AgCensus/index.php.

USDA National Agricultural Statistics Service. 2022a. "Catfish Production." Accessed at usda.library.cornell.edu/concern/publications/bg257f046.

USDA National Agricultural Statistics Service. 2022b. "Trout Production." Accessed at usda.library.cornell.edu/concern/publications/t722h882h.

USDA National Agricultural Statistics Service. 2023. "Trout Production." Accessed at downloads.usda.library.cornell.edu/usda-esmis/files/t722h882h/1v53m894q/4742bn15k/ trpr0223.pdf.

U.S. Department of Commerce NOAA. "Fisheries of the United States." May 2022. Accessed at fisheries.noaa.gov/national/sustainable-fisheries/fisheries-united-states.

U.S. Grains Council. 2018. "Reduced-Oil DDGS in Aquaculture Diets." Chapter 13 in *DDGS User Handbook*. Accessed at grains.org/buying-selling/ddgs/user-handbook/chapter-13/.

Weldon, Vanessa. 2019. "Yellow Perch Aquaculture." Accessed at freshwater-aquaculture.extension.org/ yellow-perch-aquaculture/.

Appendix: Dietary Formulation Examples for Aquatic Animals

Note. Maximum level of soybean meal established and commonly used in commercial diets for both catfish and tilapia. Both catfish and tilapia diets can be used for carp.

Exhibit A1. Channel Catfish Grower – 32% Crude Protein / 3.5% Fat

Ingredient	Inclusion rate %
Soybean meal	44.1
Corn grain	20.0
Wheat midds	16.2
Cottonseed meal	10.0
Meat and bone meal	5.0
Fish oil	2.0
Lecithin	1.5
Trace mineral and vitamin premix	0.65
Dicalcium-phosphate	0.5
Stay-C	0.05

Exhibit A2. Tilapia Grower – 36% Crude Protein / 8% Fat

Ingredient	Inclusion rate %
Soybean meal	40.0
Whole wheat	27.4
Fish meal	12.0
Meat and bone meal	8.7
Fish oil	3.0
Soy oil	2.5
Corn gluten meal	2.5
Lecithin	1.5
Dicalcium-P	1.2
DL-methionine	0.5
Trace mineral and vitamin premix	0.65
Stay-C	0.05

Exhibit A3. Rainbow Trout – Typical Formulation – 42% Crude Protein / 14% Fat

Ingredient	Inclusion rate %
Fish meal	33.5
Wheat	23.8
Feather meal	6.0
Meat and bone meal	6.0
Corn gluten meal	5.0
Soybean meal	5.0
Poultry by-product meal	5.0
Fish oil	5.0
Soy oil	4.7
Blood meal	3.0
Dicalcium-P	2.0
Lecithin	0.5
Mineral premix	0.25
Vitamin premix	0.125
Stay-C	0.05

Exhibit A4. Rainbow Trout – Modified Formulation

Ingredient	Inclusion rate %
Wheat	22.2
Soybean meal	15.0
Poultry by-product meal	12.0
Fish meal	10.0
Feather meal	9.0
Meat and bone meal	6.0
Blood meal	6.0
Fish oil	6.0
Soy oil	6.0
Corn gluten meal	5.0
Dicalcium-P	2.0
Lecithin	0.5
Mineral premix	0.2
Vitamin premix	0.125
Stay-C	0.05

Extension
University of Missouri

Issued in furtherance of the Cooperative Extension Work Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture. Director, Cooperative Extension, University of Missouri, Columbia, MO 65211 • MU Extension provides equal opportunity to all participants in extension programs and activities and for all employees and applicants for employment on the basis of their demonstrated ability and competence without discrimination on the basis of race, color, national origin, ancestry, religion, sex, sexual orientation, gender identity, gender expression, age, genetic information, disability or protected veteran status. • 573-882-7216 • extension.missouri.edu