



Assessing the Potential for Sustainable Aquaculture Development in Cambodia

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Inland capture fisheries are central to livelihoods and food security in Cambodia, but are under threat from growing anthropogenic pressures. Policy discourse in Cambodia increasingly frames aquaculture as a viable alternative to capture fisheries, and seeks to promote its development. This paper presents results from the first comprehensive survey of Cambodia's aquaculture value chain. The study combines qualitative (46 Key Informant Interviews) and quantitative surveys (1,204 farmers and 191 other aquaculture value chain actors) to investigate potential for aquaculture in Cambodia to grow, support livelihoods, and contribute to food security. We found the following: (i) The fish farm sector in Cambodia is comprised mainly of small family farms raising carnivorous fish species or pangasius, using direct inputs of "trash fish" harvested from the wild; (ii) Most fish seed and pelleted feed are imported, and domestic producers of these inputs struggle to compete; (iii) Fish farmed in Cambodia is mostly sold live. Farm fish are more expensive than the main species harvested from inland capture fisheries, and struggle to compete with imported farmed fish; (iv) Capture fisheries employ many times more people than aquaculture; (v) Space for aquaculture is limited because few locations have both perennial access to water and protection from flooding. These findings raise questions about the potential of Cambodia's aquaculture sector, as currently organized, to contribute significantly to employment, food and nutrition security, and rural economic development. We propose actions to improve the sector's sustainability and contribute to desirable development outcomes.

Keywords: Cambodia, aquaculture, food security, fisheries, food systems

INTRODUCTION

Cambodia has one of the world's most productive inland fisheries (Baran, 2005), based around the ecosystem of the Tonle Sap Lake. Inland fisheries have been central to livelihoods and food and nutrition security in Cambodia for centuries (Cooke, 2011; Sithirith, 2011), and continue to be so today (Hartje et al., 2018; Freed et al., 2020).

Aquaculture has only relatively recently become the focus of sustained interest from research and development institutions in Cambodia. This interest aligns with predicted, and increasingly realized, declines in inland capture fisheries production. For example, a combination of drought and water impoundment by upstream dams caused reported fish catch from the Tonle Sap to

contract 23% in 2020, prompting fears of imminent fisheries collapse (MRC, 2020). Such a collapse would threaten the livelihoods and food security of millions of Cambodians (IFReDI, 2013).

Aquaculture is increasingly framed in Cambodian development policy discourse as having an important role to play in meeting demand for fish and providing rural employment, but has yet to contribute significantly to these outcomes. Development projects supporting Cambodia's aquaculture sector have faced constraints to sustainable impact, and high rates of non-adoption (JICA, 2015; Richardson and Suvedi, 2018).

The relationship between capture fisheries and aquaculture is rarely discussed explicitly when aquaculture development strategies are designed or evaluated, beyond the stylized "facts" of fisheries decline and aquaculture's growth potential (Bush and Hirsch, 2005; Tezzo et al., 2020). Moreover, in common with many other countries in the Global South, little rigorous research has been conducted on aquaculture value chains in Cambodia (Bush et al., 2019). Knowledge gaps and pending development investments in Cambodia's aquaculture sector make it important to understand the characteristics of its aquaculture value chain, and to identify practical strategies that could contribute to sustainable and equitable development outcomes.

We follow the call by Tezzo et al. (2020) for a food systems approach to aquaculture development, that views aquaculture's potential to contribute to food and nutrition security in relation to capture fisheries. We combine qualitative and quantitative analysis to answer four sets of questions:

1. What is the structure of Cambodia's aquaculture value chain, and the conduct and performance of the actors in it?
2. What technical (micro) and structural (meso/macro) challenges does aquaculture in Cambodia face?
3. What is the likely future role of aquaculture in Cambodia's food system, vis-à-vis capture fisheries and with respect to food and nutrition security?
4. What options exist for supporting sustainable and equitable forms of aquaculture that contribute to livelihoods in on- and off-farm segments of the value chain?

Context synthesizes literature on fisheries and aquaculture and associated policy discourses in Cambodia. Methods sets out the methodology and analytical framework. In Results, we answer question 1 by analyzing the structure and performance of key segments of the aquaculture value chain (farms, fish seed and feed supply, fish processing and marketing). The discussion section addresses questions 2-4, with respect to prospects for aquaculture development, and implications for the design of policy and interventions. The final section concludes.

CONTEXT

Cambodia's inland fisheries are the fifth largest in the world (Fisheries Administration, 2017). Most of the fish harvested originate from the flood pulse-driven ecosystem of the Tonle Sap, Southeast Asia's largest lake. During peak monsoon season from June to October water flows upstream from the Mekong River,

filling the lake, flooding surrounding forest and rice fields, and expanding the Lake's surface area from 0.25 million hectares to 1-1.3 million hectares. From November-February, water from the lake flows back toward the Mekong, causing the water level to fall (van Zalinge et al., 2003).

Half of rural Cambodian households fish, on either a regular or occasional basis (Nasielski et al., 2016) catching >200 kg of fish per year on average, of which more than half is sold (Mousset et al., 2016). In addition, many households migrate to the Tonle Sap river during peak fishing season to purchase fish for transformation into fermented fish paste (LeGrand et al., 2020).

Consequently, fish and other aquatic animals are the main animal source foods eaten in Cambodia (Olney et al., 2009; IFReDI, 2013), accounting for three-quarters of animal protein intake, second only to rice in terms of total food intake, and rich in micronutrients. Fisheries are particularly important for the food and nutrition security of poorer households with insufficient resources to invest in farming or aquaculture (Roos et al., 2007a; Chhoun et al., 2009; Nam and Touch, 2011; Hartje and Grote, 2016). This includes the 19% of rural families that are landless, and the 40% of farm households that own <0.5 ha of land (World Bank, 2006).

Cambodia's inland fisheries face a variety of threats. Hydropower development in the Mekong catchment is expected to reduce fisheries production by up to 42% (ICEM, 2010; IFReDI, 2013). Hydropower dams and smaller-scale infrastructure such as roads, canals, and irrigation dams reduce seasonal water flows including the flood pulse that feeds the Tonle Sap ecosystem, disrupting aquatic habitat connectivity, and blocking movements of sediment and fish migrations (Baran et al., 2007; ICEM, 2010; Basist and Williams, 2020). Agricultural intensification is driving use of chemical inputs, irrigation (Mukherji et al., 2009), and aquatic habitat conversion (Mahood et al., 2020). Destructive fishing practices are widespread (Chan et al., 2020).

These threats are compounded by more frequent droughts linked to climate change. Severe droughts in 2016, 2019, and 2020 caused large catch declines, altered fish species assemblages, and drove shifts in fish size composition toward smaller fish (Ngor et al., 2018; Chan et al., 2020; FISHSTAT, 2020). Higher temperatures and changes in rainfall and river flows are predicted to affect water quality, particularly impacting migratory fish species (ICEM, 2013).

As a result, Cambodia's capture fisheries are predicted to be unable to meet future demand, with negative implications for human nutrition (IFReDI, 2013; Golden et al., 2019). Fish supply is predicted to fall by 34,000–182,000 tons (6 to 34%) depending on the number of dams built on the Mekong mainstream, equivalent to a drop in fish consumption from 63 kg/person/year in 2011 to between 41 and 29 kg/person/year (IFReDI, 2013).

Despite vast differences in the current scale of the inland capture fisheries and aquaculture sectors in Cambodia in terms of quantities of food produced and numbers of people engaged, there is a common tendency to depict capture fisheries as "traditional" and locked in a trajectory of terminal decline, in contrast to aquaculture which is framed as a "modern" sector on the rise (Bush, 2008; Friend et al., 2009; Arthur and Friend,

2011; Tezzo et al., 2020). This framing has the effect of making aquaculture appear as a logical and inevitable substitute for capture fisheries.

Policy strategies increasingly prioritize aquaculture development. For example, the government of Cambodia's Agricultural Sector Strategic Development Plan for Fisheries targets increasing aquaculture production by 20% per year (MAFF, 2015). A National Aquaculture Strategy (2016–2030) aims to identify investments to fill the “supply gap” in fish and develop a sector that contributes significantly to economic growth and generates employment (Fisheries Administration, 2019). These strategies have drawn inspiration from neighboring Thailand and Vietnam, which are among the world's top 10 aquaculture producers (FAO, 2018).

Development aid worth more than USD 59 million was granted to Cambodia's aquaculture sector between 2016 and 2019; more than three times the total invested in the sector from 2000 to 2015¹. Capture fisheries also remain a primary recipient of donor investment in Cambodia, with EUR 87 million allocated from an EU-Cap Fish Capture project, but only a fraction of these resources are used to support active fisheries management, while a significant share is dedicated to upgrading fish processing, and providing alternative livelihoods to fisheries dependent households.

Although policy discourse invokes a promising future for Cambodian aquaculture, implementing projects have encountered multiple challenges. Ex-post-evaluations report these to include inadequate access to quality inputs (VCA4D, 2017; Richardson and Suvedi, 2018); weak technical skills among farmers (Chin, 2015; Bengtson et al., 2016); and limited access to water (Maredia et al., 2017; Richardson and Suvedi, 2018). As such, these studies ascribe low levels of aquaculture adoption mainly to micro-scale farm level constraints, amenable to technical solutions such as training or input provision.

Meso- and macro-scale economic, political, and environmental dimensions that are more difficult to assess are often overlooked in such evaluations. For example, interactions between supply and demand of Cambodian inland capture fish, imported farmed fish from Vietnam and Thailand, and Cambodian aquaculture products are poorly understood and rarely acknowledged. Discussion of the links between capture fisheries and aquaculture focuses mainly on competition for use of small low-cost fish (“trash fish²”) for human consumption or as fish feeds (Nam et al., 2005). The physical suitability of the

Cambodian environment for aquaculture, in terms of access to perennial water and flood risk, is often absent from the debate.

We address the micro-scale technical concerns and meso/macro-scale structural ones outlined above using primary data from a comprehensive survey of Cambodia's aquaculture sector. The survey methodology is elaborated below.

METHODS

We surveyed 1,204 farmers and 191 other actors in the aquaculture value chain in nine provinces and Phnom Penh municipality from April to July 2019 (WorldFish, 2019). Provinces were selected purposively based on triangulation between key informant interviews and provincial statistics, and include all the main areas where commercial inland aquaculture production occurs.

Quantitative Sampling Method and Data Collection

We implemented a scoping study in these provinces prior to the survey to estimate the population of fish producers and other aquaculture value chain actors. Subsistence farmers and micro-scale producers were deemed out of scope, and farms with a pond area <200 m² or a cage volume <30 m³ were excluded. Fish traders and processors for whom products sourced from aquaculture accounted for at least 20% of raw material were considered in scope. This exercise identified a total population of 1,617 farms and 406 other value chain actors eligible for inclusion in the survey.

We initially designed a random sample of 1,200 farmers. During survey rollout we found that some respondents had stopped aquaculture, had been selected incorrectly, or could not be contacted. We therefore switched to an exhaustive sampling strategy for farms. The sample represents more than 85% of all active aquaculture producers in the surveyed provinces that met our selection criteria.

We selected a sub-sample of other value chain actors, with the following criteria, per province: (i) all operational feed mills; (ii) three micro-finance institutions; (iii) three fish feed distributors; (iv) three fish wholesalers; (v) five fish collectors (mobile traders); (vi) 30% of fish processors; (vii) all operating hatcheries (30) and nurseries (9). The final sample consisted of 1,204 farms (including 690 pond farms, 504 cage farms and 10 farm operating both types of system), and 191 other actors: 30 hatcheries, nine nurseries, eight feed mills (all of which, at the time of the survey, produced livestock and/or poultry feed but no aqua feed), 24 feed distributors, 34 fish processors, 69 fish traders, and 17 microfinance institutions. We later excluded from the analysis 96 farms that did not report any production in the 12 months preceding the survey, nine farms that operated both ponds and cages, and three farms that reported the type of farm (pond or cage) inconsistently. The questionnaire covered the calendar year 2018 through May 2019 and included modules on assets, employment, farm management practices, and quantities of fish produced and sold in the 12 months preceding the survey.

¹2016–2019 period: Three large projects: EU-AFD Cap Fish Aquaculture = €30 million granted in 2016 until 2021; Sustainable Aquaculture and Community Fish Refuge Management (SAFR) of the German Ministry for Economic Cooperation and Development operated by GiZ granted in 2019 until 2023 with a budget of €4.5 million; USDA Food for Progress funding CAST project USD17 million in 2018. Total approximate USD 59 million funding of granted during this period. From 2000 to 2015 –we count few significant aquaculture projects: JICA FAIEX phases I and II (2005–2015) for a total of USD 8.7 million and USAID HARVEST program (2010–2016) for a total of USD 56 million but including a support to several sectors (rice, horticulture, fisheries, and aquaculture). We estimate the funds dedicated to aquaculture to around USD 10 million.

²“trash fish” is a common term used to denote small, low market value fish that are utilized as feed for farmed fish or animals. This can include food grade fish that would otherwise be edible to humans.

Data were collected on the farm or at business premises during interviews with farmers and business owners (for other value chain actors) by a survey team composed of five enumerators and a supervisor. All data were collected on digital tablets using the KoBo Toolbox platform.

Typology of Farms and Descriptive Statistics

A data cleaning protocol was used to check for inconsistencies or abnormal responses, to generate a clean dataset (WorldFish, 2019). Excel 2016 and R software were used for data analysis to produce descriptive statistics on farm and business performance. We constructed a simple typology of farms based on the distribution of pond and cage farm sizes within the total population, distinguishing three size-based categories of pond and cage farms (“small,” “medium,” and “large”) as follow:

- Small pond farms (<500 m²) and small cage farms (<50 m³)
- Medium pond farms (500 to 3,000 m²) and medium cage farms (50 to 100 m³)
- Large pond farms (>3,000 m²) and large cage farms (>100 m³)

The cage farm categories can be interpreted as roughly equivalent to number of cages per farm (1, 2, ≤3) given an average cage volume of ~50 m³, whereas the pond farm categories are constructed to include a roughly equal number of farms in each group.

We estimated the amount of trash fish used within our sample based on recall data. For homemade feed with trash fish, we use an average ratio of 20% of trash fish per kilogram of feed to estimate the volume of trash fish used in farms (Nam et al., 2005). Extreme values were excluded from the calculation.

Qualitative Sampling, Data Collection, and Analysis

In addition to the quantitative survey described above, we collected qualitative data to capture contextual information, with an emphasis on private service provision, quality control systems, and relationships governing coordination between actors in the value chain. Key informant interviews were conducted with 46 value chain actors, government representatives, development partners, and fish retailers. The interviews were recorded and translated in English before coding using NVivo 12 software. After coding was completed, the team produced node reports that were further analyzed to identify emerging themes.

The results section below combine both qualitative and quantitative results. We use the quantitative survey results to assess the performance of different segments of the value chain and the qualitative interview results to provide context and add nuance to the interpretation of the results of the quantitative survey. In the results section, all information derived from qualitative interviews is identified as such.

RESULTS

We analyze the following value chain segments in the order indicated: (1) producers (pond farms and cage farms); (2) input supply (hatcheries, nurseries, and feed suppliers); (3) traders and processors of farmed fish.

Producers

Using a simple typology of farms, we evaluate the structure of the farm segment of the value chain, with respect to production systems, farm size distribution, location, and water use. We then evaluate the conduct (feeding practices) and performance (productivity) of pond and cage farms for the three most common fish species cultivated in each.

Farm Structure

Our typology distinguishes three size-based categories of pond and cage farms (“small,” “medium,” and “large”; **Table 1**). Surveyed fish farms average 2,369 m² (ponds) and 114 m³ (cages) in size, respectively. This is small compared to other countries in the region. For example, in nearby Central Thailand pond farms range from 1 to 100 ha with farms around 2–3 ha most common, and small and medium cage farms are sized 180 and 915 m³, respectively (Belton et al., 2009). Thus, what we refer to here as “large farms” are large relative to other farms in Cambodia, but small relative to farms in some other parts of Southeast Asia.

Figure 1 illustrates the location of surveyed farms, over-layed with the extent of flooding in 2011, a major flood year. Cage farms are located around the edges of the perennial Tonle Sap waterbody and on major rivers that enter and exit the lake, indicating a requirement for continuous water throughout the year. Pond farms are located mainly in a narrow band close to national roads running around the outer edge of the area exposed to flooding. Half (49%) of pond farms lie within the area that flooded in 2011 and can thus be considered at risk of flooding. Most land outside the Tonle Sap floodplain is drought prone. Pond farms appear to be clustered in locations that combine adequate access to water and transport with protection from heavy flooding. This spatial distribution highlights the limited extent of areas suitable for aquaculture production.

Pond farms are the dominant form of production, supplying around 80% of farmed fish. Production is concentrated among farms at the upper end of the size distribution. Only large farms operate more than two ponds or cages each, on average. Farms in our “large” category each make up around 18% of pond and cage farms, but account for 71 and 67% pond and cage area and 70 and 52% of pond and cage fish production, respectively. Although farms in our “small” category account for one third of pond farms and more than half of cage farms, they amount only 5 and 16% of pond and cage farm area, and supply 6 and 25% of pond and cage farm production, respectively (**Table 1**).

Most farms are managed intensively. For example, the average extrapolated yield for pond farms is equivalent to 43.7 t/ha and 35.5 kg/m³ for cage farms. Smaller farms are most productive. For example, the yield of small cage farms is 52.1 kg/m³, as compared to 27.8 kg/m³ for large cage farms.

TABLE 1 | Pond and cage farm characteristics.

Type of farm	Size range	n	% of farms	Mean size	Share farm area (%)	Number of ponds/cages per farm	Quantity of fish produced (t)	Share of fish produced (%)	Average production per farm (t)	Yield	Main source of water (% farms)	
											River	Rain
Pond (all)	m ²	665	100	m ²	100	1.50	6,889	80	10.37	t/ha	45	25
Small	<500	239	36	311	5	1.11	415	6	1.73	55.8	36	30
Medium	500–3,000	312	47	1,211	24	1.46	1,654	24	5.30	43.7	48	23
Large	>3,000	114	17	9,857	71	2.41	4,819	70	42.64	42.8	57	20
Cage (all)	m ³	431	100	m ³	100	1.37	1,751	20	4.06	kg/m ³	-	-
Small	<60	222	52	36	16	1.13	417	24	1.87	52.1	-	-
Medium	60–100	126	29	67	17	1.28	418	24	3.31	49.5	-	-
Large	>100	83	19	396	67	2.17	915	52	11.02	27.8	-	-

All cages are located in natural waterbodies. The main sources of water for pond farms are rivers (used by 45% of farms) and rainwater 25%. Only 8% of farms use groundwater irrigation. Larger farms are somewhat more likely to use river water, and small farms are slightly more likely to be rain fed. As a result, many pond farms are vulnerable to drought, climate variability, and competition for surface water. Key informant interviews confirmed that many producers face water shortages in the dry season, and that surface water pollution by industry and agriculture is increasing. Farms in or near waterbodies or within the floodplain can have easier access to surface water and be less dependent on rainfall, but are vulnerable to flooding. Pond farms in such locations require investments in dikes and/or netting to avoid fish escapes.

Farm Conduct and Performance

In this subsection we analyze farm conduct (farming technologies, and farmer behavior regarding input purchases and product sales) and performance (yields). We analyze the most common species produced in pond and cage farms, by farm size category. Surveyed farms produced 12 species in total, but five dominated, accounting for 97% of the volume. 88% of the farms specialize in production of a single species.

The main fish species raised in cages are carnivorous. Striped snakehead (*Channa striata*) and giant snakehead (*Channa micropeltes*) are most popular, raised by 56 and 26% of cage farms, respectively. The high value species, Asian red tail catfish (*Hemibagrus wyckioides*), is produced mainly by large cage farms (5% of cage farms). Pangasius catfish, an omnivorous species, is the main fish cultivated in ponds (53% of pond farms) and is also raised in 10% of cage farms. Giant snakehead is also found in both types of farm, and raised by 35% of pond farms Silver barb is present in 12% of pond farms (Table 2). Other species, including tilapia, carps, hybrid walking catfish, climbing perch and snakeskin gourami are produced by 8 and 7% of surveyed pond and cage farms, respectively. Spatial distribution of the main cultivated species is uneven, except for pangasius, which is found in every province (Figure 2, map A to F).

Pangasius accounts for 61% of the total quantity of fish produced by farms in our sample, followed by giant snakehead (25%) and striped snakehead (7%). Snakehead and catfish species are farmed much more intensively than silver barb (Table 1). Reported yields are within the range of previous estimates (WorldFish, 2010), suggesting that productivity has not improved significantly in the past decade. Average yields of pangasius grown in ponds (53 t/ha) are several times lower than in Vietnam (370 t/ha) (Belton et al., 2011).

Most farms purchase fingerlings from nurseries or traders. These businesses often import fish seed from Vietnam informally. As an indicator, 35 and 31% of farmers acknowledged that the giant snakehead and striped snakehead seed they stocked was imported from Vietnam. Among farms growing pangasius and silver barb in ponds, only 13 and 19% respectively reported buying their fingerlings from hatcheries in Cambodia, with 35% of silver barb fingerlings obtained from NGOs. <2% of the cage farms reported stocking wild caught fingerlings.

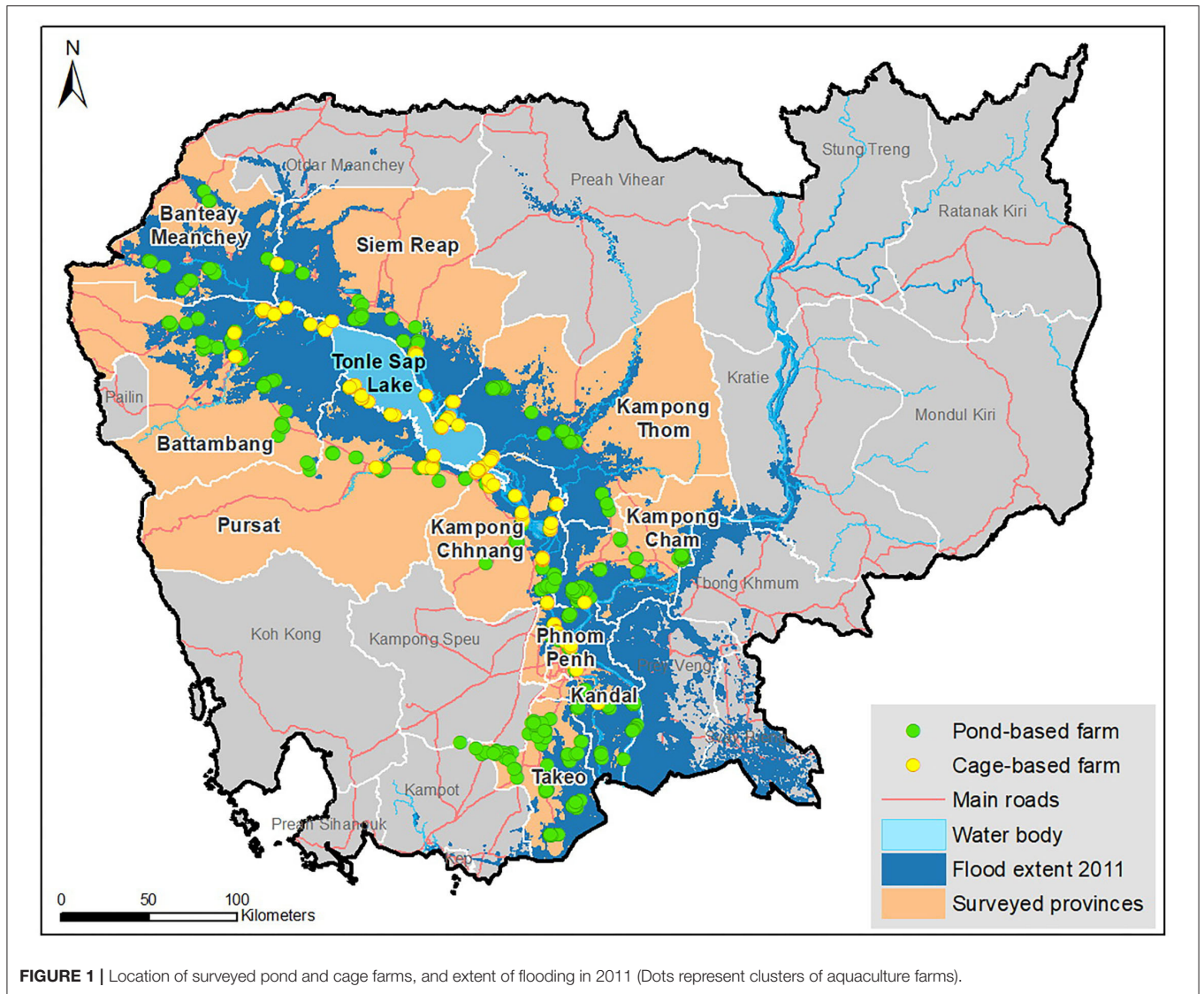


FIGURE 1 | Location of surveyed pond and cage farms, and extent of flooding in 2011 (Dots represent clusters of aquaculture farms).

TABLE 2 | Pond and cage farm characteristics by species.

Type of farm	Yield	Share of total production (%)	Sales value	Fingerling source (%) [*]		Number of cycles per year	Harvest lasting longer than 4 days	
				Trader/nursery	Local hatchery			
	<i>n</i>		USD/kg				(% farms)	
Pond	t/ha	78						
Pangasius	305	53.0	57	1.24	74	13	0.97	47
Giant snakehead	199	77.0	20	2.21	93	1	0.95	21
Silver barb	68	5.6	1	2.14	35	19	0.91	41
Cage	kg/m³	18						
Striped snakehead	250	52.0	7	1.39	99	0	1.04	5
Giant snakehead	114	36.7	4	1.97	86	3	0.96	10
Pangasius	45	29.0	3	1.36	49	9	0.96	38
Red-tail catfish	20	23.9	2	3.12	57	0	0.81	48

^{*}Only the two main fingerling sources are presented.

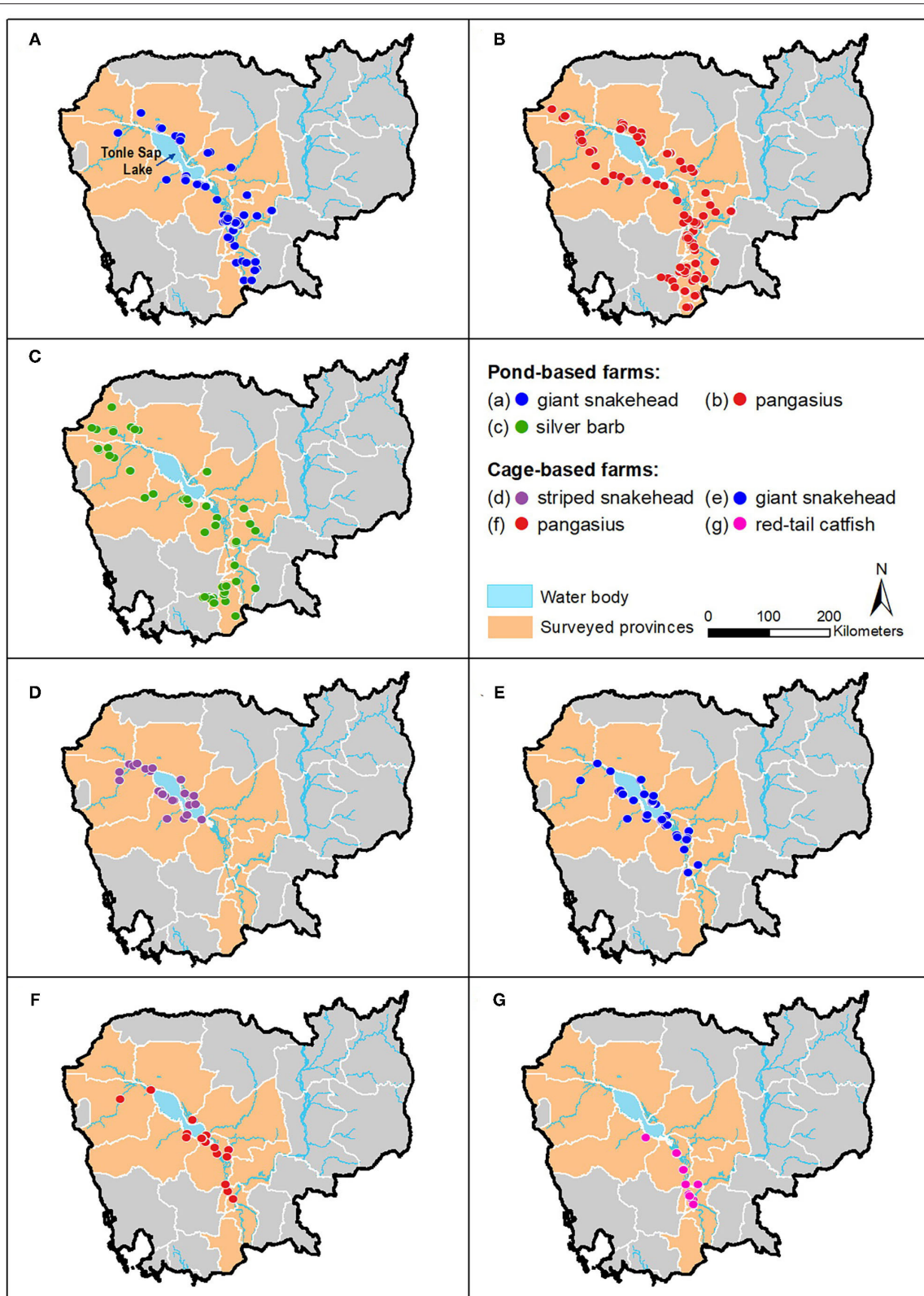


FIGURE 2 | Location of pond and cage farms by fish species. Pond farms: **(A)** giant snakehead; **(B)** pangasius; **(C)** silver barb. Cage farms: **(D)** striped snakehead; **(E)** giant snakehead; **(F)** pangasius; **(G)** red-tail catfish.

Production cycles are annual, with close to one cycle completed each year. Average farm gate prices vary by species, ranging from USD 3.12/kg for red tailed catfish to USD 1.24/kg for pangasius. Pangasius farmers reported that local prices are influenced strongly by the volume of cheap imported pangasius from Vietnam. Farmers often time their harvest according to the fluctuating price of imported fish. When prices are too low, they extend the harvest over 10–20 days, waiting for better prices. Harvest duration is also influenced by consumer demand for live fish, which is sold daily in limited volumes. Many farms spread their harvest over multiple days due to low demand, thus increasing stress and mortality of fish. Extended harvests can also raise production costs, as fish continue to require feed.

Most farms use “trash fish” in some form, either exclusively, in combination with other feeds, or as an ingredient in farm-made feed (Table 3). Most trash fish is comprised of small, low cost, food grade fish species, harvested locally from the inland capture fishery. All snakehead farms use trash fish. Most giant snakehead farms use trash fish exclusively (81% of ponds and 61% of cages), as do 42% of striped snakehead cage farms, possibly suggesting that striped snakehead domestication is more advanced than giant snakehead, making the former more readily weaned onto artificial feeds.

None of the farms surveyed use manufactured pelleted feed exclusively. However, its use is common among pond farms, and those growing pangasius. For example, 87% of pangasius pond farms and 73% of pangasius cage farms use pellets. Conversely, trash fish use is somewhat less common among pond farms—51% of pangasius pond farms use trash fish in some form, as compared to 80% of pangasius cage farms. We hypothesize that for cage farms, proximity to the Tonle Sap Lake and rivers makes trash fish easily accessible. However, snakehead pond farms are also heavy users of trash fish showing that access to trash fish is not necessarily constrained by distance from fishing grounds.

We estimate that farms in our sample used 13,400 tons of trash fish in the survey year. This is equivalent to ~0.9 kg of fish for every person in Cambodia. Pond farms and cage farms use 58 and 42% of the total quantity of trash fish utilized, respectively. Smaller farms are more likely to utilize trash fish—perhaps harvesting it themselves to save costs—and are less likely to purchase manufactured pelleted feeds. Larger farms are more likely to buy pellets—perhaps in part because it is difficult to obtain trash fish in sufficiently large quantities, or expensive to use if not self-harvested. This pattern is consistent across pond and cage farms and could indicate a partial transition toward more sustainable farming practices among larger farms (Figure 3).

Input Supply

This section we analyze the scale of operations and conduct of actors in upstream fish seed and fish feed supply segments of the value chain. We surveyed 30 hatcheries and nine nurseries, representing all hatcheries and the largest and most active nurseries in the survey area.

Fish Seed Supply

The existence of a competitive domestic fish seed production sector is widely regarded as essential for aquaculture

development to occur successfully, as the availability of affordable, high quality seed is a key factor conditioning farm performance (Tran et al., 2021).

Surveyed hatcheries produced a total 26 million fingerlings in 2018 (Figure 4), a relatively low total volume of production. For comparison, tilapia hatcheries in Thailand sold around 80 million fry per month in 2008 (Belton, 2012), and Vietnam produced more than 2 billion pangasius fingerlings in 2019 (VASEP, 2020). The number of fingerlings produced per surveyed hatchery in Cambodia ranges from 5,000 individuals to 7 million, with eighteen hatcheries producing fewer than 0.5 million fingerlings each year. The main species produced are tilapia, pangasius and silver barb, accounting for 40, 36 and 10% of fingerlings, respectively. This species composition differs considerably from that reported by surveyed farms.

Fish seed production is highly seasonal as rainfall determines the timing of stocking on farms, peaking in the monsoon months of July and August. Only 45% of hatcheries reported being able to meet demand for seed during the peak stocking period. Key informant interviews explained this result with reference to the short peak in demand requiring production of large quantities of seed within a brief window, and limited production planning and no marketing strategies to reach new markets beyond their established networks.

Many hatcheries and nurseries face severe environmental constraints. Rain is the main source of water for 43% of hatcheries, putting them at risk of water shortages. 43% of hatcheries also reported having been affected by severe drought in the recent past. A female nursery operator in Phnom Penh mentioned: “Another constraint is the irregular rain that makes fish become sick or die.” However, 33% of hatcheries are regularly affected by floods, requiring fencing around ponds to avoid brood fish escaping and mixing populations. Half of nurseries also reported being affected by flooding.

Linkages between hatcheries and nurseries are limited. According to key informant interviews, nurseries do not usually contract Cambodian hatcheries as seed suppliers, as the supply of seed from local hatcheries is considered unreliable and expensive. Nurseries buy and sell seed with a short nursing period, averaging 28 days, and therefore operate more as fingerling traders than conventional nurseries. Most of the seed traded by nurseries is imported from Vietnam. The nine surveyed nurseries traded 38 million fingerlings in 2018. This is almost double the amount sold by all 30 hatcheries in our sample, underlining the importance of nurseries selling imported seed in supplying Cambodia’s fish seed market. The main species traded by hatcheries and nurseries are pangasius (38% of the volume), walking catfish³ (38%) and giant snakehead (19%).

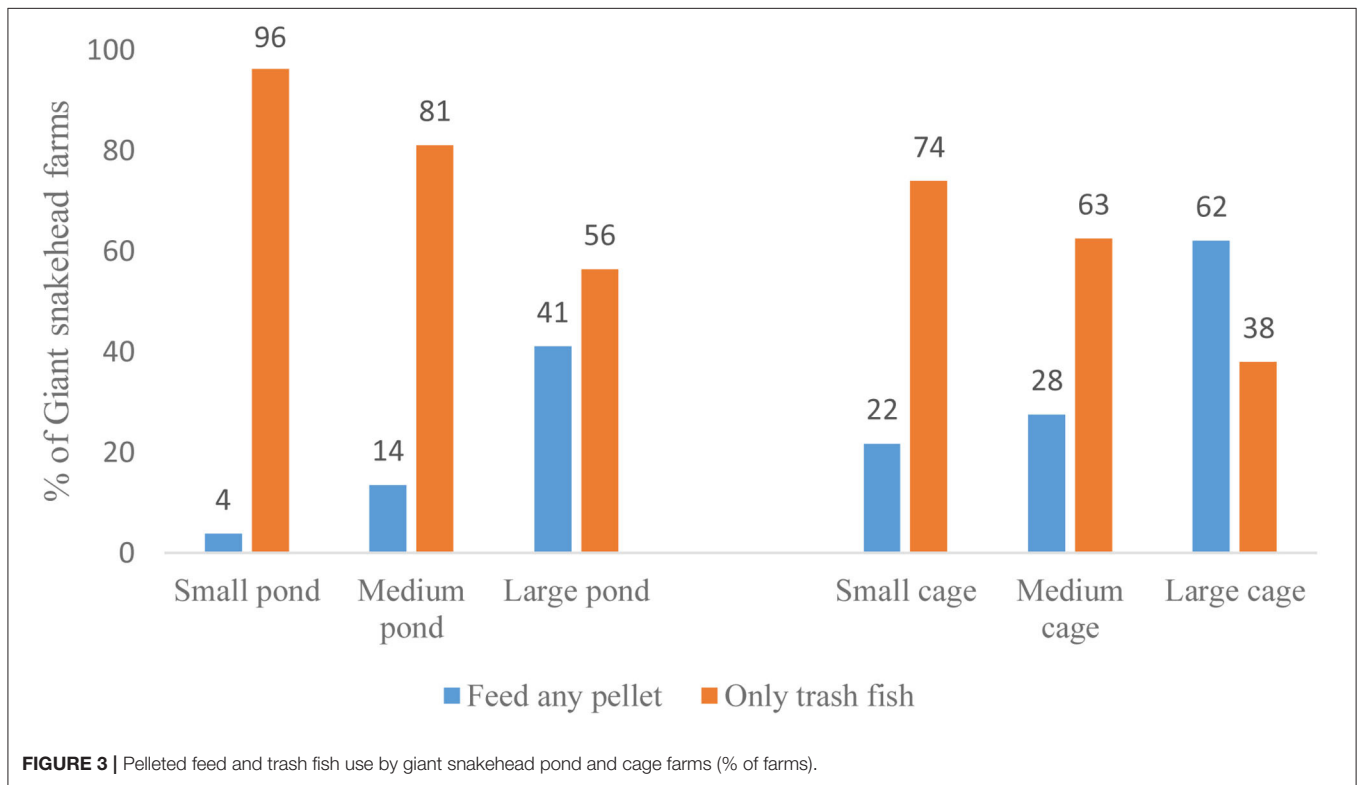
Ten nurseries in Cambodia have a license to import fingerlings (VCA4D, 2017). Our sample only included licensed nurseries, but according to our key informant interviews unlicensed nurseries probably contribute a large share of snakehead seed imports, and some unlicensed nurseries sell

³Walking catfish does not feature as a major species in our farm survey because it is mainly produced in extremely small farms that fall outside the scope of our sample.

TABLE 3 | Feeding practices of pond and cage farms, by species (% of farms)*.

Type of farm	n	Commercial pelleted feed	Homemade feed with trash fish	Homemade feed, no trash fish	Trash fish only	Trash fish + other feed	Trash fish (in any form or combination)
Pond	665	61	15	27	30	45	57
<i>Giant snakehead</i>	229	15	5	3	82	99	100
<i>Pangasius</i>	348	87	26	30	3	30	51
<i>Silver barb</i>	80	79	4	64	1	4	8
Cage	430	52	12	3	40	85	95
<i>Striped snakehead</i>	250	56	9	0	42	92	100
<i>Giant snakehead</i>	115	34	4	1	61	98	100
<i>Pangasius</i>	45	73	20	9	2	67	80
<i>Red-tail catfish</i>	21	29	38	10	14	62	90
ALL	1,095	57	14	18	34	61	72

*One farm can have multiple feeding regimes. Bold values represent results for all pond, all cage farms and entire sample.



wild fingerlings on a seasonal basis. A recent government survey suggested that 47% of fingerlings are imported from Vietnam, 40% produced locally and 10% sourced from the wild (CaPFish Baseline Survey, 2020). Our own study indicates that 78% of farms sourced fingerlings from nurseries that mostly sold imported seed. On this basis we estimate that well-over half the seed used in Cambodian aquaculture is imported. As such the sector is currently dependent on imported seed, over which local actors and decision makers have little influence, especially regarding quality control.

Fish seed sold in Cambodia does not meet basic quality standards in terms of minimum size, homogeneity, and pathogen free status. <20% of hatcheries and 12% of nurseries grade fingerlings before sale to ensure uniform size. Only 30% of hatcheries report checking for parasites, and only 43% follow basic hygiene practices such as sterilizing equipment after spawning.

The average size of fingerlings sold is just 3.5 g each. There are no regulations for the fingerling trade, neither for tracing origin, nor specifying quality. Fish seed sales are made through networks of clients with trusted relationships.

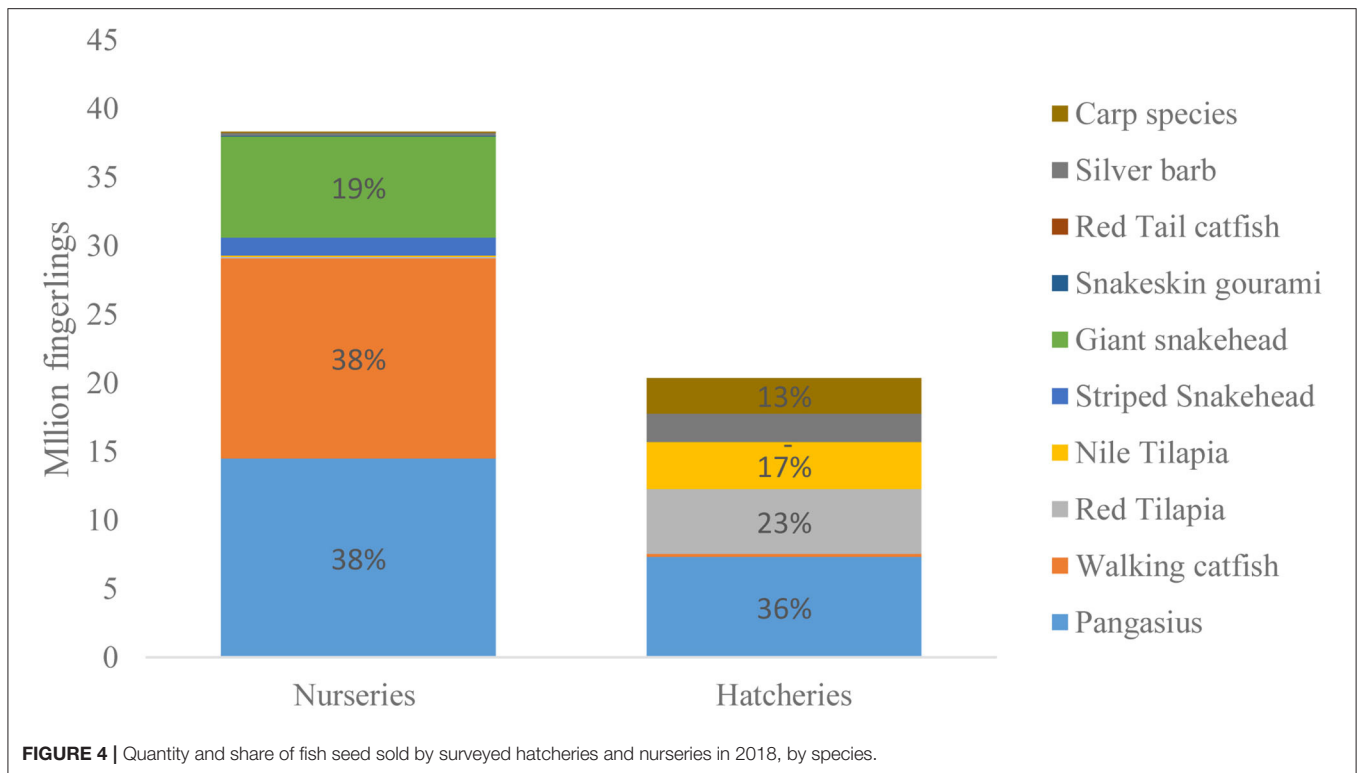


FIGURE 4 | Quantity and share of fish seed sold by surveyed hatcheries and nurseries in 2018, by species.

Fingerlings supplied by surveyed nurseries consistently sell for 20–60% <those sold by local hatcheries. For example, pangasius fingerlings available from nurseries, which are presumed to be imported, sell for USD 0.02 per piece, whereas those supplied by local hatcheries cost USD 0.024.

Fish Feed Supply

No fish feed mill was operating in Cambodia at the time of the survey, but one local feed mill began to produce floating pellets in 2020. All floating pelleted fish feed sold in Cambodia at the time of the survey was imported, from Vietnam and Thailand. Six brands of imported floating pelleted fish produced by large feed companies are marketed through a network of retailers. Retailers sell feed mainly during peak farming season from July to December, with average sales of 20 tons each during this period, but with wide variations (1.5 to 91 t). About half (45%) of feed retailers have a contract with a feed manufacturer that specifies a minimum annual sales target.

Feeds for pangasius and walking catfish are the best-selling items and priced from USD 0.61–0.87/kg. This is somewhat higher than in neighboring Vietnam and Thailand, but does not appear excessive, considering the transport and transaction costs associated with importing feeds. In fact, given the relatively small size of the aqua-feed market in Cambodia, the presence of six international brands suggests a convenient market for international suppliers operating on a large-scale in neighboring countries, resulting in a reasonable level of competition. Nevertheless, key informant respondents stated that to produce fish at a price that could compete with imported fish, they would need to buy feed costing around USD 0.50/kg, which is similar

to pangasius feed prices in Vietnam. However, this estimation does not take into account the other relative advantages that Vietnamese farms have, including economies of scale.

Post-harvest Value Chain Segments

In this section, we analyze the processing and trading segments of the aquaculture value chain, focusing on product types, quality standards, and prices. Our sample included 69 fish traders (a mix of “collectors”-mobile traders who aggregate fish, and wholesalers who operate from fixed premises in markets), and 34 fish processors (producing dried, smoked and fermented fish products), all using raw material comprised of a minimum of 20% Cambodian farmed fish.

These businesses are small and medium enterprises, trading an average of 169 tons of fish per trader, and purchasing an average of 19 tons of fish per processor annually. They operate with limited assets. For example, only three wholesalers (or 10% of our sample) owned a refrigerator, and no “modern” industrial or semi-industrial processing of farmed fish was observed.

The main farmed fish traded are snakeheads, walking catfish, and pangasius. Traders reported procuring 68% of the farmed fish they traded from Cambodian farms and the rest from imports. Processors obtained 33% of the fish they processed from Cambodian farms, with the rest from the wild or imported.

Much of the farmed fish sold in Cambodia is marketed live, including both locally produced and imported farmed fish. The main farmed species (snakeheads and catfishes) can breathe atmospheric oxygen and can survive for long periods with little or no water making live marketing relatively simple. 60% of the farmed fish traded by surveyed traders was sold live,

through outlets including landing sites, wholesale markets and wet markets. Live sales serve as a guarantee of freshness, and live fish attract a higher average sales value than dead fish. The preponderance of live sales means that reported rates of spoilage are low, at just 6%. Only 27% of Cambodian farmed fish was reported to be sold in fresh, dead form. This was mainly used for producing high value processed products such as dry salted giant snakehead, and smoked walking catfish, but these processors also purchase live fish.

The volume of fish imported by Cambodia in 2017 was estimated to be 120,000 tons, based on a review of import licenses (VCA4D, 2017). Another recent survey indicated that 46% of farmed fish traded in Cambodia was imported (CAST, 2020). Most imported fish are farmed pangasius from Vietnam. Fish are usually imported live, regardless of species. Import volumes fluctuate depending on the ability of Vietnamese producers to export to higher value markets (VCA4D, 2017). The price offered by traders to Cambodian fish farmers is benchmarked against the price of imported fish.

Our qualitative interviews suggest that these conditions are challenging for Cambodian fish farmers, as illustrated by a medium scale male farmer from Kampong Cham producing pangasius who stated *“the price (of farmed fish) is not stable, it declines when the imported fish from Vietnam enters the market.”* Similarly, another medium scale pangasius farmer operating in Battambang mentioned: *“The problem is that a lot of pangasius remain unsold since there are a lot of imported fish from Vietnam. A lot of imported fish from Vietnam entered (Cambodia) recently, so the local fish prices declined.”*

Common species of small wild fish harvested around the Tonle Sap Lake, such as gourami or medium and small sized cyprinids, tend to be more affordable than farmed fish from any source, costing approximately half as much at between 0.66 and 0.88 USD/kg (Mille et al., 2016), and contributing disproportionately to fulfilling demand for fish by poorer households.

In sum, most farmed fish marketed in Cambodia currently occupies one of two specific market niches—live fish, or high value processed fish—both of which face stiff competition from Vietnamese live fish imports. To date, neither locally produced nor imported farmed fish can compete on price with small wild fish harvested from the Tonle Sap, which continue to be the mainstay of consumption by lower income consumers.

Quality Standards and Product Differentiation

Surveyed producers, traders, and processors did not report adhering to the hygiene procedures promoted by extension services and development projects. Moreover, supermarkets do not impose their own quality standards on suppliers. Qualitative interviews highlighted that although processors are aware of the existence of good practices, they are reluctant to implement them due to the costs involved, and lack of premiums for higher quality products.

The qualitative survey indicated that demand for locally produced fish is high, due to a positive perception among

Cambodian consumers about Cambodian products. Cambodian-farmed fish are considered of higher quality than imported fish because of the perception that fewer antibiotics and hormones are used in their production. Consumer ranking of preferences for fish places Cambodian wild fish first, followed by Cambodian farmed fish, with imported farmed fish least preferred.

Several respondents indicated that there is an emerging market for higher quality products (certified safe product, chemical free) in urban areas, as some consumers are becoming more willing to pay higher prices. This was illustrated by a male wholesaler operating in Pursat who stated, *“even though we sell our local fish at a higher price, people still buy our fish. Even though imported fish is sold at cheap prices, buyers would not buy it if they knew it was imported.”*

Supermarkets, restaurants, and caterers stressed the need for a quality standard traceability system, as wealthier consumers, particularly in urban areas, are increasingly aware of food safety issues. These respondents felt that the inability to distinguish between local and imported products was causing missed business opportunities for producers to access markets and to gain higher selling prices. A restaurant manager in Siem Reap made mention of quality control regulations: *“Sometimes the laws (guidelines and regulations) have already been established, but we do not understand what’s in them, so it’s more like everything is okay.”*

However, developing a quality standard traceability system faces several constraints. First, it requires a regulatory framework and the institutional capacity to enforce such regulation. In addition, there is limited interest from wet market retailers, who account for most fish sales, in implementing a system of quality standards as the establishment of a will result in premium prices, making fish more difficult to sell. The current perception among most actors is that live fish are an adequate indicator of quality. As described by a female wholesaler in Pursat: *“Live fish means that fish is good quality. No one questions about fish quality; as long as fish are alive, fat and available in the market, those fish are good.”*

Employment Generation and Livelihoods

Current development discourse frames aquaculture as a potentially significant source of jobs and income for rural Cambodians. To gain a sense of the scale of aquaculture’s current contributions to rural employment and livelihoods in Cambodia, we estimated levels of family and wage employment generated by businesses included in our survey. Several results stand out.

First, surveyed enterprises currently generate limited employment, totaling 5,052 full time employment equivalents (FTEs), assuming 240 person days of employment per year (Table 4).

Second, businesses in the aquaculture value chain currently generate few opportunities for hired labor, reflecting the micro- or small-scale of most of the enterprises involved. 85% of FTEs within our sample (4,296 FTEs) are family employment. Only 15% (756 FTEs) are paid work.

Third, family labor FTEs are evenly split between women (50%) and men (50%). Women and men participate in family labor in roughly equal proportions in all segments of the value chain except nurseries, where women are somewhat

TABLE 4 | Employment of family and hired workers by surveyed farms and businesses*.

	Hatcheries	Nurseries	Farms	Traders	Processors	Total
<i>n</i>	28	9	1,204	69	33	1,343
Full-time family labor/enterprise	3.1	2.9	3.2	5.9	2.6	–
Full time hired labor/enterprise	0.5	0.4	0.2	3.1	1.3	–
Casual labor (total FTEs)	53	11	14	139	52	269
Fulltime hired FTE's	24	5	283	121	54	487
Of which, women (%)	25	18	6	19	59	–
Family FTE's	88	26	3,900	197	85	4,296
Of which, women (%)	47	38	46	93	54	–
Total FTEs	165	42	4,197	457	191	5,052

*Average number of person employed per farm/company and Full Time Equivalent (FTE). Full time employment is estimated based on 240 working days per year.

underrepresented (accounting for 38% for FTEs). Most family labor is deployed on farms, which are the most numerous category of enterprise in the value chain, accounting for 90% of family labor FTEs.

Fourth, most casual paid employment is concentrated in the midstream segments of the value chain (trading and processing), which trade and/or process fish from both capture fisheries and aquaculture. As we are unable to differentiate between work related to products from each source, these figures overestimate aquaculture-linked paid employment among surveyed businesses. The limited number of fulltime workers employed by hatcheries, nurseries, and farms reflects the small size of these enterprises, and is indicative of a lack of professionalization and low levels of skilled labor in the sector.

Fifth, men are the main beneficiaries of paid employment in Cambodia's aquaculture value chain. Most paid work is generated on farms, where men account for 94% of hired FTEs. Women dominate fish processing, accounting for 59% of hired FTEs, but their representation as hired workers in trading, hatcheries and nurseries is more limited ($\leq 25\%$ of hired FTEs).

DISCUSSION

In this section we discuss the implications of results presented above with respect to (1) technical and structural challenges for aquaculture development, (2) capture fisheries-aquaculture interactions, and (3) aquaculture's potential to support livelihoods and employment.

Technical and Structural Challenges to Aquaculture Development

Results presented above indicate that systemic transformation would be required to achieve the ambitious policy targets set for Cambodia's aquaculture sector. We identify constraints at the farm (micro) and sector (meso/macro) scale, across technical, institutional, economic, and biophysical dimensions. At the scale of the production unit (farms, hatcheries, processors), our study reconfirms the existence of technical and economic constraints highlighted in previous studies. These include limited access to water on farms, the high price of feed and poor quality of seed, and the basic nature of most farming practices (Bengtson et al., 2016; Maredia et al., 2017; VCA4D, 2017; Richardson and Suvedi,

2018; Joffre et al., 2019). However, unlike previous studies, we also identify a three fundamental sector-wide structural challenges to the growth of Cambodia's aquaculture sector.

First, there is limited regulation and lack of enforcement of the import of fish and fingerlings from neighboring countries. Prices of imported fish reflect their lower production costs, and it is suspected that fish that are unfit for export due to residues, or surplus to demand in major markets find an outlet in Cambodia (VCA4D, 2017).

This issue is currently being addressed by the government with a temporary ban on imported aquaculture fish to support local industry (MAFF, Press release on January 08 2021). However, the legality of this ban remains unknown, as Cambodia is part of the ASEAN community and trade barriers are subject to WTO treaties. Import controls would better be approached from a food safety and biosecurity perspective, to avoid unregulated imports of material of unknown quality. Similar issues arise from the import of large numbers of fingerlings of unknown origin, health status, and quality (Joffre et al., 2019).

Second, there is no regulatory framework to control the quality of domestic farmed fish products. The absence of standards, quality certification, or traceability systems means that producers and processors have little incentive to upgrade their practices. A lack of such indications also makes it difficult to differentiate domestically produced fish from imported fish of unknown quality, limiting the ability of Cambodian producers to expand their domestic market share. Establishing formal standards would also be a prerequisite prior to targeting export markets in the medium-term.

However, the likelihood implementing greater standardization remains questionable in the current context, where standards will increase operating costs, making it more difficult for producers to compete with imported fish on price. Implementation of missing or unenforced regulations would be more effective if based on local capacity and coordinated with existing regulations in the agriculture and livestock sectors. Without adequately enforced regulations in place, there will be few incentives for hatcheries and producers to make the investments in their operations needed to bring about quality improvements.

Third, the study highlights the extent of spatial and temporal constraints on aquaculture development in Cambodia. We find

that most pond-based farms, and many hatcheries and nurseries, face annual drought and flood cycles. Although Cambodia is often depicted as a country with abundant water resources, many producers are affected by drought, often limiting production to the rainy season. To be more competitive, the aquaculture production cycles could complement the seasonality of capture fisheries. Currently the highest catch volume occurs at the same time as the end of the aquaculture production cycle from January to April. To avoid such competition and target the harvest during the period of low catch fish catch (June to September), producers, hatcheries, and nurseries will need access to water to start their production cycle earlier in the dry season, when water is often scarce. Groundwater is rarely used as a water source for pond farms and hatcheries, meaning that exploring methods to ensure affordable groundwater access by fish producers could represent a key policy option.

Although hydropower dams currently limit the flood pulse in the Tonle Sap Lake, Cambodia and the Tonle Sap region can still be heavily flood affected (Sabo et al., 2017). In addition to the survey reports of flooding of pond farms, hatcheries, and nurseries, in October 2020, a severe flood event occurred, impacting thousands of households, including numerous fish farms, resulting in thousands of dollars in losses to aquaculture farmers (CAST, 2020). This fact highlights the persistent vulnerability of the sector to flood, and the need for new financial products such as aquaculture insurance as a risk mitigation tool for investors.

Interactions Between Capture Fisheries and Aquaculture

Capture fisheries provide most of the fish supply for rural Cambodians. Although pressures on inland fisheries productivity are increasing, including recurrent weak flood pulses in 2016, 2019, 2020 (Basist and Williams, 2020; MRC, 2020), our study suggests that Cambodia's aquaculture value chain is unlikely to fill the fish supply gap given current standards of conduct and performance. Aquaculture yields are relatively low, producers are dependent on imported inputs, and production systems are based on carnivorous species that are still highly dependent on capture fisheries for their feeding regime.

Thus, the common discourse of a national aquaculture sector replacing capture fisheries to sustain the supply of fish is unlikely to be realized soon. It is more likely that a continued decline in the productivity of the inland capture fishery would reinforce dependence on imported aquaculture products, especially during months when local aquaculture production is limited.

A major shift in the origin of fish in the human diet could have negative consequences for human health. Shifting consumption from diverse fish species sourced from capture fisheries, including many micronutrient-rich small fish species, to few larger less nutrition farmed fish species could negatively affect nutrient intake and dietary quality (Roos et al., 2007b; Lachat et al., 2018; Bernhardt and Connor, 2021). For example, in Bangladesh research has shown that although the growth of aquaculture has mitigated the supply-demand gap caused by the decline in inland captures fisheries, it has not fully compensated

for reduced loss of dietary diversity and micronutrient intakes (Belton et al., 2014; Bogard et al., 2017).

The current affordability of farmed fish, relative to capture fish, is also questionable. The average farm gate pangasius price is above USD 1.20/kg, and 41% of the volume produced is sold above USD 2.00/kg, while other farmed fish produced in Cambodia are considerably more expensive than this on average. In contrast, in rural areas, prices of fish common fish species from capture fisheries are often well-below that threshold (Mille et al., 2016), especially during the main harvesting season of most aquaculture production systems. Moreover, recent studies show that a significant share of fishing households near the floodplain do not sell any of their fish catch, relying on this resource for household food security (Freed et al., 2020).

Hence, the affordability of aquaculture fish to low-income consumers could be a barrier to replacing the affordable fish sourced from capture fisheries. In addition, it has been estimated that only 2% of animal source food consumed in Cambodia originates from aquaculture, as compared to 49% sourced from inland capture fisheries (Vilain and Baran, 2016). Although aquaculture's share has likely grown since this estimate was produced, especially given importance of farmed fish, these figures underline the magnitude of the current gap between the two sectors in terms of their contributions to livelihoods and food and nutrition security.

Our data also show that Cambodia's aquaculture sector is still heavily dependent on "trash fish" with an estimated 13,400 tons of trash fish used for feed during the survey year. Considering predicted declines in inland fisheries productivity and increasing competition for fish between aquaculture and human consumption, the reliance of the sector on local trash fish is a distinct limiting factor for future growth. Fisheries decline would increase trash fish prices, and push producers to convert their farms to production of non-carnivorous fish species, or change their feeding regime by using manufactured pellet, combined with domestication of snakehead and giant snakehead. Large farms are already changing their practices and using more pelleted feed compared to small farms. We expect that producers will soon have to shift their feeding regimes, or increase the pace of this transition, similar to the changes observed in the striped snakehead sector in the Mekong Delta where producers shifted toward pelleted feed with the increasing price of trash fish (Sinh et al., 2014).

Competition between human consumption and aquaculture for low-priced fish is likely to intensify, if fish catches decline further. Already in 2020, record low Dai fisheries catches resulted in a 72% increase in the price of fish harvested compared to 2019 (FAO, 2020; MAFF, 2020). Meanwhile, even if public and private sector investments enable a shift to the use of pelleted feed, the transition to use of manufactured pellets is likely to take several years. Therefore, reliance on trash fish to feed aquaculture fish will remain in the near-term. Meanwhile, existing carp, silver barb and tilapia production systems could intensify by using fertilizer and rice bran and feeding regimes based on pond ecology. However, demand for these fish is low at present.

Based on these findings, we conclude that domestic aquaculture could be complementary to capture fisheries,

rather than a replacement. Like in Bangladesh, where capture fisheries was also a pillar of the rural population's food security, a growing aquaculture sector might meet part of the growing demand and mitigate the impact of declining capture fisheries (Belton et al., 2014). However, unless the current production costs of aquaculture production systems (reflected by the selling price at the farm gate) can be reduced significantly, farmed fish is likely to remain less affordable than lower value capture species have been in the past.

Until or unless the sector develops further, and input prices are reduced, aquaculture in Cambodia will continue to respond to demand within specific niches, with the growing middle class in urban areas the preferred target. With an urban population representing 23% of the population and a steady annual growth rate above 3% per annum (World Bank, 2020), urbanization is likely to become one of the main drivers for aquaculture sector.

Potential Contributions to Employment and Livelihoods

Our results show that Cambodia's aquaculture sector is comprised of family-farms and businesses, with limited employment generation outside the family. Within our sample, 90% of labor is family based and fewer than 5,000 full-time equivalent jobs were generated.

Based on the 2019 census of the rural population (NIS, 2019) and the estimated number of households engaged in aquaculture, we estimate that $<1.5\%$ ⁴ of rural households are engaged in aquaculture (including small scale low input systems), compared to 10% of the population engaged full time fishing and 35% employed part time fishing (Ahmed et al., 1998).

These findings align with previous studies highlighting the magnitude of difference in employment between capture fisheries and aquaculture. For example, Mousset et al. (2016) showed that for households in rural Cambodia, aquaculture accounts for a labor input of 0.09 FTE per household, compared to 1.12 FTE per household for capture fisheries.

It is estimated that between 2 million and 4 million people are engaged full-time in fisheries, with an official figure of 2.3 million currently used (Fisheries Administration, 2017). Thus, although decline of fisheries might push a fraction of fishers to enter aquaculture, such a transition would be conditional upon prerequisites such as investment capacity, access to land, and skills, and would not compensate fully for lost employment in capture fisheries.

The apparently rather limited employment generation potential of aquaculture in Cambodia at present also reflects a lack of opportunities for skilled labor for farms and hatcheries. Educational programs for aquaculture are currently limited in Cambodia: there is no vocational training curriculums and academic programs in aquaculture are of low quality (Schkepper, 2019). Expanded vocational training to support the development of a skilled workforce for farms and hatcheries could thus help

to improve the employment generation capacity of the sector, as well as its performance.

CONCLUSIONS

This study is the first comprehensive assessment of Cambodia's aquaculture sector. The study has some limitations. Even though our sampling strategy was exhaustive, recently emerging large commercially oriented farms may be underrepresented. Data collection based on recall did not permit precise analysis of production system performance, especially regarding feed use, where the main raw material for feed is trash fish. Further specific on-farm monitoring surveys will be required to analyze the performance of farms under different feeding regimes. Regarding the analysis of the value chain conduct, the linkages and flows of trash fish between capture fisheries and aquaculture should be investigated further and volumes estimated more accurately. Finally, we did not assess financial performance of the different production system and compare the competitiveness gap with similar production systems operating in neighboring countries.

This study highlights that Cambodia's aquaculture production systems remain constrained by technical, institutional, and economic factors that limit their performance and competitiveness. To achieve the transformation of the aquaculture sector, several macro-scale structural interventions are required, among which the development of a regulatory framework for regulating imports of fish, fingerlings and inputs to Cambodia is key. This also encompasses developing value chain standards to differentiate imported and local farmed fish and respond to increasing demand for locally raised fish.

Commercially oriented fish farming will grow only with perennial access to water and if flood risk is mitigated. Considering the effect of hydropower development on flood patterns (Basist and Williams, 2020), the overall hydrology of the country and climate change predictions in the region (ICEM, 2013) that forecast higher temperatures and longer dry seasons, affordable access to groundwater may be required for aquaculture to grow further. In addition, aquaculture cannot be established, nor expand everywhere in the country and investments should be prioritized to target aquaculture clusters in suitable areas, where support systems, producers and concentrations of other value chain actors exist and can be supported.

In terms of aquaculture inputs and farming practices, our analysis shows that feeding regimes are still heavily dependent on trash fish from capture fisheries, which are increasingly scarce. The transition toward the use of formulated feeds will be facilitated by access to good quality pelleted feeds at a competitive prices, and to knowledge to support efficient feeding practices. Our recommendations regarding feed include creating an enabling environment (e.g., a regulatory framework, accurate information on market demand, and market information systems) for feed producers to invest in local production lines. A widespread shift of feeding regime will also require the transformation of support services, with more accessible sources of information to facilitate behavior change among producers toward more sustainable practices

⁴Our estimation is based on 2019 census of the rural population (12,561,921 persons) divided by the average household size (4.6 person per household) and the estimated number of households engaged in aquaculture in 2020: 40,609 households (MAFF, 2020).

using less trash fish. In addition, the ecological intensification of pond systems producing non-carnivorous species through semi-intensive feeding regimes based on pond ecology, green water, and rice bran could also support increased production.

Skilled labor is required facilitate a transition to more efficient value chains and production systems. Trained professionals with practical skills will be needed to provide support services to producers and support sectoral development. Donor-funded projects initiated since 2020 are training farmers and private service providers and supporting access to knowledge. However, additional support and more fundamental changes in access to education, knowledge and support services for the sector are required to support its transformation.

It will prove increasingly difficult for inland capture fisheries to meet future demand for fish in Cambodia, given the growing range of anthropogenic pressures they face, and likely increases in demand for fish from an urbanizing population. This dynamic suggests an important role for aquaculture in Cambodia's food system in years to come, but as a complement to capture fisheries, with respect to food and nutrition security, livelihoods, or employment, not as a substitute for them. Cambodia's aquaculture sector currently faces a unique set of structural and technical challenges. Addressing the areas for intervention listed above, while working to minimize any further pressures on inland capture fisheries productivity are both necessary steps to ensuring that this complementary role can be realized.

GENERAL STATEMENT

Prior to the survey all respondents were provided with an oral informed consent statement in Khmer (or English for key informants who were fluent in English and interviewed in English) and asked for their consent before the interview (both qualitative and quantitative survey). In Cambodia there is no established procedure for ethical review process for socio-economic research. However, the local authorities reviewed the

survey questionnaires. No sensitive topics or vulnerable human subjects were involved.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the dataset is under the license of the Commercialization of Aquaculture for Sustainable Trade (CAST) Project. Access to the dataset requires a specific data agreement with the American Soybean Association. Requests to access the datasets should be directed to James Bernhardt, JBernhardt@soy.org.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

OJ, SF, and JB: designed the study. SF performed the quantitative analysis. OJ, SF, and BB: interpreted the results and drafted the article. ST conducted the GIS analysis. All authors contributed to revising and approving the manuscript.

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