FEED THE FUTURE
The U.S. Government's Global Hunger & Food Security Initiative

RFA-FIL-19-000001: Harnessing Machine Learning to Estimate Aquaculture Production and Value Chain Performance in Bangladesh

Fish Innovation Lab

Final Technical Report April 1, 2020 – September 30, 2022

Cooperative Agreement 7200AA18CA0030

USAID
FROM THE AMERICAN PEOPLE

MISSISSIPPI STATE UNIVERSITY™
GLOBAL CENTER FOR AQUATIC HEALTH AND FOOD SECURITY

Harnessing Machine Learning to Estimate Aquaculture Production and Value Chain Performance in Bangladesh

Final Technical Report
April 1, 2020 – September 30, 2022

Cooperative Agreement 7200AA18CA0030

[December 12, 2022]

Prepared by:
[Ben Belton, Md. Mahfujul Haque]

This report is made possible by the generous support of the American people provided by the Feed the Future Innovation Lab for Fish through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. The Feed the Future Innovation Lab for Fish is managed by Mississippi State University through an award from USAID (Award No. 7200AA18CA00030; M. Lawrence, PI) and provides support to Grant No. RFA-FIL-19-000001: B. Belton, PI

Partners/Institutions

Michigan State University

Bangladesh Agricultural University

International Center for Tropical Agriculture

WorldFish

Abbreviations and Acronyms

Acronym	Meaning
BAU	Bangladesh Agricultural University
CIAT	International Center for Tropical Agriculture
Co-PI	Co-Principle Investigator
DOF	Department of Fisheries
FAO	Food and Agriculture Organization of the United Nations
FIL-ME	Fish Innovation Lab Management Entity
FtF	Feed the Future
GCFSI	Global Center for Food Systems Innovation
GIS	Geographic Information System
GDP	Gross domestic product
IT	Information Technology
MEL	Monitoring Evaluation and Learning
M&IE	Meals and Incidental Expenses
MSU	Michigan State University
NGO	Non-Governmental Organization
ODK	Open Data Kit
PI	Principle Investigator
USAID	United States Agency for International Development
WEAI	Women's Empowerment in Agriculture Index

Table of Contents

Contents

Executive Summary

Lack of rigorous data collection means that 'conventional wisdom' about aquaculture often lags far behind conditions on the ground, and makes aquaculture production statistics unreliable. Inadequate information makes it difficult to plan and manage aquaculture development, or design investments, policies, and interventions effectively. Moreover, new technologies and practices developed by innovative farmers and supply chain actors often go unrecognized, and may diffuse more gradually than they would do if promoted actively by formal extension agents. Digital technologies are undergoing a revolution. Artificial intelligence (machine learning), remote sensing, smartphones, mobile internet, social media, and opensource data collection and video production software open up an array of new possibilities for cheaply collecting, analyzing and communicating information in new forms, to multiple audiences. Drawing together all these strands, we combined survey based research techniques with remote sensing, machine learning, and video production, to generate knowledge products disseminated via digital media to reach and serve the diverse information needs of farmers, enterprises, researchers and government. The project had three goals:

First, identify emerging technologies and innovative practices in aquaculture value chains and pilot digital extension approaches that accelerate their adoption, while reducing transaction costs and time associated with traditional forms of technical research and extension. **Second**, use machine learning to automate extraction of data on ponds from satellite images and integrate with georeferenced survey data to accurately estimate fish production, economic value, and employment (disaggregated by gender and age) to improve the accuracy of official statistics and enhance capacity to effectively target investments and regulation. **Third**, build organizational and individual capacity in Bangladesh for conducting rigorous research on socio-economic and spatial dimensions of aquaculture, and contribute to a more enabling environment for fostering sustainable aquaculture growth. The project was comprised of three components: (1) Surveys; (2) Remote sensing; (3) Capacity building.

Component 1 followed the 'stacked survey method' developed by Michigan State University to survey a total sample of 1195 value chain actors in seven districts in the Feed the Future Zone of Influence in Southern Bangladesh, comprised of 66 hatcheries, 79 feed suppliers, 721 farmers, 229 fish traders and 100 fish retailers, around 75% of which were interviewed by MSU in 2013. Additional in depth interviews were used to gather detailed information on their practices, and produce short videos featuring individuals talking and demonstrating their innovative behavior in their own words to provide easily relatable content to be disseminated widely through social media platforms. **Component 2** utilized machine learning to extract and analyze data on fishponds from satellite images. Combined with data collected under Component 1, this analysis facilitated development of an interactive online data visualization tool used to estimate aquaculture's multi-dimensional contributions to the economy and nutrition, focusing on production, economic value added, and employment, all differentiated by gender. The publicly available web-based tool was designed based on stakeholder consultations to facilitate user interaction with and visualization of the data generated. **Component 3** was dedicated to formal training and outreach to build individual, organizational, and societal capacity. This included: (1) Stakeholder consultations on features potential users wished to see incorporated into the interactive GIS interface. (2) Data collection and analytics capacity building training to build host-country researcher capacity for quantitative survey data analysis, analytical thinking and written and oral academic presentational skills. (3) Dissemination of Bangla language extension videos via social media. (4) An online six-part remote sensing capacity building course for GIS users (5) Three closing workshops to promote new and emerging technologies to private sector actors and extension agents at national level and in the surveyed zones.

Introduction/Justification

In 2013 Michigan State University (MSU) directed a 'stacked' survey of around 2500 value chain actors in Bangladesh - the most comprehensive aquaculture value chain survey conducted anywhere in the world (Hernandez et al, 2018)[1]. The stacked survey methodology was designed to address knowledge gaps and statistically test empirical hypotheses in a way that the stakeholder and key informant interviews typically adopted by value chain studies cannot. The survey revealed a "quiet revolution" taking place in aquaculture value chains in Bangladesh – changes in the numbers and behavior of farms and supporting enterprises occurring on a scale that had not previously been observed or quantified.

Lack of rigorous data collection efforts in most developing countries means that 'conventional wisdom' about aquaculture often lags far behind conditions on the ground, and makes aquaculture production statistics unreliable. Inadequate information makes it difficult to plan and manage aquaculture development or design investments, policies, and interventions effectively. Moreover, new technologies and practices developed by innovative farmers and supply chain actors often go unrecognized by formal extension agents, and diffuse more gradually than they would do if promoted actively.

Digital technologies are also undergoing a revolution, in terms of computational power, cost, and accessibility. Artificial intelligence (machine learning) has developed very rapidly in recent years. The resolution and public availability of datasets of remotely sensed satellite images have also improved dramatically. Meanwhile, advances in digital data collection using cloud-based software on tablets, have made collection of georeferenced household survey data the norm. The cost of producing digital video content has also declined dramatically, with the advent of high-resolution mobile phone cameras and open source video editing software. Expansion of internet connectivity, widespread adoption of smartphones, and high levels of engagement with social media open up new possibilities for mass communication that offer the potential to reach large audiences cheaply and effectively through the placement of well-designed content, even in rural Bangladesh.

Drawing together all these strands, we combined survey based research techniques with machine learning to generate knowledge products that were disseminated via digital media to reach to serve the diverse information needs of farmers, enterprises, and government planners.

The project had three goals:

First, identify emerging technologies and innovative practices in aquaculture value chains and pilot digital extension approaches that accelerate their adoption to enhance productivity, efficiency, resilience, and human nutrition, while reducing the transaction costs and time associated with traditional forms of technical research and extension.

[1] Hernandez, R., Belton, B., Reardon, T., Hu, H., Zhang, X., Ahmed, A. 2018. The "Quiet Revolution" in the Aquaculture Value Chain in Bangladesh. *Aquaculture*. 493: 456-468

Second, use machine learning techniques to automate extraction of data on ponds from satellite images and integrate with georeferenced survey data to accurately estimate fish production, economic value, and employment (disaggregated by gender and age), with the intent of improving the accuracy of official statistics and enhancing capacity for targeting investments and regulation (e.g. zoning, farm registration, traceability).

Third, build organizational and individual capacity in Bangladesh for conducting state of the art research on socio-economic and spatial dimensions of aquaculture development, and contribute to societal capacity to create a more enabling environment for fostering sustainable aquaculture development.

Research focused on seven districts, selected based on relevance to USAID programming, and importance for aquaculture. All the districts are located in the USAID Feed the Future (FtF) Zone of Influence, where FtF funded activities are concentrated. Districts selected for resurvey account for three quarters of pond area and production in Khulna division and close to two thirds of fish production in Barisal Division, as estimated using figures published by DOF (2017)[2].

Research Methods

The project was comprised of three components: 1) Surveys; 2) Remote sensing; 3) Capacity building. Component 1 (Surveys) and Component 2 (Remote Sensing) employed distinct but complementary research methods. These are outlined as follows:

Component 1 followed the 'stacked survey method' developed by Michigan State University. This survey method entails a full statistically representative sample survey of actors at every major segment of the aquaculture value chain (namely; hatcheries, feed suppliers, farmers, fish wholesalers and fish retailers). This approach makes it possible to collect data that is far more comprehensive and accurate than that yielded by conventional approaches to value chain research, which are typically based on small numbers of key informant interviews, or to deploy non-representative samples that bias results. The survey questionnaires asked each set of actors five categories of question:

(1) Characteristics of the actor, in particular, the types of assets held (gender, age, human capital such as education; social and organizational capital such as membership in associations and cooperatives; physical capital such as holdings of ponds, equipment, land, and vehicles);
(2) Factor inputs (use of hired and family labor, and external non-labor inputs such as seed, feed, fertilizer and fuel) and intermediate inputs (such as the inventory bought by a trader), in terms of costs, geographic origins, input specifications (e.g. types of feed and chemicals, species and strains), supplier types, value chain finance, quality attributes, and any contractual relations;
(3) Value addition using the inputs plus technology to produce outputs, such as production of fish, delivery and marketing of products, cold storage; and

[2] DOF. 2017. Yearbook of Fisheries Statistics of Bangladesh. Fisheries Resources Survey System (FRSS), Department of Fisheries, Bangladesh. Volume 33: 124 p.

(4) Marketing of the outputs (in terms of prices received, geographic destinations, and buyer types, as well as value-chain finance, quality attributes, contractual relations, labeling/branding, food handling practices and food waste.)
(5) A modified version of the Women's Empowerment in Agriculture Index (WEAI) tool, originally developed for USAID by the International Food Policy Research Institute[3], was used to obtain a metric of women's control over assets, decision making and income associated with aquaculture.

We used the sample of farms and businesses surveyed by MSU in 2013, resurveying all farms and businesses that could be contacted, and adding randomly selected replacements here attrition had occurred between survey rounds. Conducting a 'panel survey' in this manner was intended to facilitate tracking changing practices over the intervening period, and to identify emerging technologies to be further disseminated and scaled up through video based interventions.

Questionnaires were developed for each value chain segment, based on questionnaires developed in 2013, but modified to account for weaknesses identified during analysis of data collected during that survey, and to include additional questions and modules on areas of particular interest in the context of the present project. This included the addition of a WEAI module, and additional questions of labor and employment, including the gender and age of family and hired labor, that will allow for estimates of aquaculture's contribution to employment at the zonal level, and questions of food safety and anti-biotic use. We also collected data on crop production from integrated farming systems (e.g., rice-fish, fish-prawn-vegetable) allowing us to estimate differences in the production of nutrients emanating from different cropping systems.

Questionnaires were pre-tested in the field and modified extensively prior to the actual survey by team of several enumerators, two research assistants, and a research coordinator. Digital versions of the questionnaire underwent further rigorous pre-testing. Prior to survey implementation, a team of enumerators (university students and recent graduates) underwent an intensive two-week training comprised of a mix of classroom and field based activities. Data cleaning activities were led by a CIAT research assistant, and by a PhD student registered at BAU, and working at WorldFish.

Additional in depth semi-structured interviews were used to gather detailed information on new and emerging technologies and trends, and individual actors (farms, hatcheries, feed suppliers, traders) who have adopted them. These interviews will provided the basis for filming short videos featuring individuals demonstrating and talking their innovative behavior in their own words, on their farms or business premises. Individuals selected for participation in the videos included a mixture of women, men, youth, and older people. The videos were intended to be easily relatable to a wide range of other potential users of these technologies, and were posted on a dedicated 'Aquaculture TV' Facebook and YouTube site developed by the project, to be shared widely among interested parties. Key research findings will be published in peer-reviewed journal articles after project completion. A number of draft articles have already been completed, or close to completion.

Component 2 used machine learning techniques to extract and analyze data on land use cover (specifically, fish ponds) from satellite images. Combined with data collected under Component 1, this analysis facilitated the development of an interactive online data visualization and

[3] https://www.feedthefuture.gov/the-womens-empowerment-in-agriculture-index/

decision support tool that reports estimates of aquaculture's multi-dimensional contributions to the economy and nutrition, focusing on production, economic value added, and employment, differentiated by gender. Component 2 was comprised of three phases.

- **Phase I:** a dataset of remotely sensed images (e.g., Sentinel-1 SAR) and indices (e.g., NDWI and MNDWI) was be selected, and initial parameters for image extraction and analysis were be set (i.e., the spatial and visual characteristics used to define ponds of different types, such as homestead ponds, intensively managed ponds, extensive shrimp ponds, integrated rice-fish or rice-prawn systems). These initial decisions provided inputs for a machine learning algorithm programmed to identify and measure aquaculture waterbodies. Following a series of initial iterations during which the algorithm's performance was be constantly refined, locations in Bangladesh were selected randomly and visited to ground truth data on land use cover and pond types. More than 1800 datapoints were recorded. This information was used to train the algorithm to produce more accurate results.

  Phase II: information derived by machine learning during phase one was used to estimate the area of aquaculture waterbodies in each of the seven districts. Estimates of the area of ponds in each zone were combined with georeferenced survey data (e.g., pond productivity, gross margins, employment multipliers) to generate estimates of fish production, economic value-added, and job creation by gender, representative at the level of each of the districts surveyed. A further innovation developed during the project was a methodology to estimate the productivity of key nutrients from different integrated aquatic farming systems Southern Bangladesh.

- **Phase III**: a publicly available web-based decision support tool was developed to facilitate user interaction with the data generated. Specifications for the interface were decided based on a stakeholder consultation (see next section on capacity building) to maximize its utility to end users. The decision support tool enabled visualization of pond area and numbers of farms (as estimated by machine learning) at the district level, as well as volumes of production by species, on-farm employment, and economic value added. This approach allowed for comparison with official data on farm area, production and productivity, as reported by DOF.

  For each surveyed district the decision support tool presents the following data: **(1)** Production (yield per unit area and total quantity produced) by species group (shrimp, prawn, carp, tilapia, others), technology (e.g., feed use), and production system (e.g., type of integration with terrestrial crops). **(2)** Gross margins and economic value added (per unit area, and as aggregate economic output). **(3)** On-farm demand for family and hired labor (number of individuals employed, and full-time employment equivalents), and wages rates disaggregated by gender and age group will be provided for every data array (e.g., the value of economic output attributable to women and men; youth as a share of workers or business operators in each value chain segment).

  The methodology and codes developed were made publicly available, with the express intent of encouraging uptake of the project's approach to the measurement of aquaculture impacts by researchers in other national settings. Key findings on the remote sensing and machine learning techniques have already been published in two high impact peer-reviewed journals.

Individual capacity building for project staff occurred though guided “learning by doing”, and was central to all components of the project, through close mentoring of host country researchers and enumerators.

Component 3 was dedicated to a range of more formal activities that sought to build individual, organizational and societal capacity. These are listed and elaborated in chronological order below.

1. An online half-day stakeholder consultation was convened to share preliminary machine learning/remote sensing findings from Component 2, introduce the concept behind the interactive decision support tool, and elicit feedback from potential users on features they wished to see incorporated into its design in order to maximize practical utility. Stakeholders included officers from the fisheries statistics division of the Department of Fisheries, and GIS experts from the Bangladesh Agricultural Research Council, NGOs, and several universities.

2. We originally planned to hold an intensive data analytics capacity building retreat following the completion of survey implementation and data cleaning activities, to be attended by all Bangladesh-based project researchers, and a small number of carefully selected research analysts and students from BAU. This proved impossible due to COVID-19 travel restrictions, and because most project enumerators and research assistants joined were unavailable following the survey due to participation in civil service entry exams and taking up new jobs. We therefore focused on building the analytical skills of the project PhD student, Hazrat Ali. Ali did exceptionally well in this role, rapidly learning to use STATA software to analyze survey datasets. As of project closeout he had completed a full set of descriptive statistical tables for all major surveys, except for the hatchery survey, which is in progress at the time of writing. Ali has already completed two advanced draft papers based on these results, for submission to Aquaculture and Food Policy. This performance is exceptional and is evidence of highly effective individual capacity building

3. Short Bangla language extension videos developed under Component 1 were disseminated through a dedicated ‘Aquaculture TV’ Facebook and YouTube page established by host country PI Haque, to build capacity to adopt new technologies and speed up the uptake of improved practices among farmers and other value chain actors. Video clips developed by the project were promoted widely through these outlets to encouraging sharing of content.

4. Building on the information dissemination activities listed under item three above, one-day workshops were held in Dhaka (hosted by DOF at DOF headquarters), and in Khulna and Gopalganj (two of the districts surveyed), contributing to societal and institutional capacity building. The workshops were designed to inform government and private sector stakeholders of key project findings and policy recommendations, and explain the methodologies deployed. Senior DOF officials, extension workers, and owners of farms and enterprises that participated in the survey were invited to participate, providing a forum to discuss both the advantages and challenges of innovative practices with peers and allowing participant to learn directly from one another. Extension videos developed by the project,

and the online decision support tool were presented during these events, to build capacity through promoting informal peer-to-peer interactions and information sharing.

5. An in-person five-day remote sensing capacity building course was originally planned to take place in Dhaka with participation from Michigan State University co-PI Nejadhashemi. This proved impossible due to COVID-19, so an online course was designed, featuring six instructional videos averaging 45 minutes in length, with six online interactive drop in sessions with the training course creator, Hannah Ferriby, from Michigan State University. The course attracted 136 participants, among whom 92 from Bangladesh, and 30 women.

Research Results

We present summaries of key research results below by subject area.

(1) Development of machine learning techniques for identifying aquaculture waterbodies

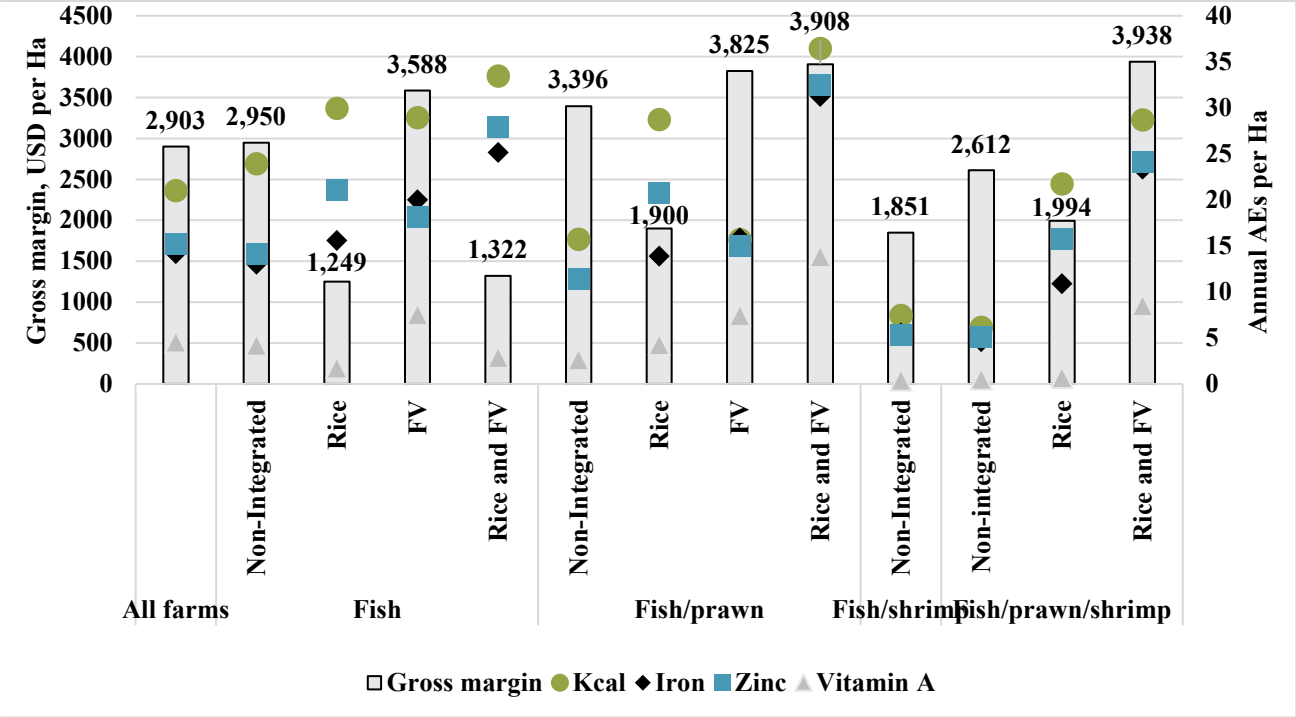
Using Sentinel-2 top of atmosphere reflectance data within Google Earth Engine, we proposed six different strategies for improving fishpond detection as the existing techniques seem unreliable. These techniques include: (1) identification of the best time period for image collection, (2) testing the buffer size for threshold optimization, (3) determining the best combination of image reducer and water-identifying indices, (4) introduction of a convolution filter to enhance edge-detection, (5) evaluating the impact of ground truthing data on machine learning algorithm training, and (6) identifying the best machine learning classifier. Each enhancement builds on the previous one to develop a comprehensive improvement strategy called the enhanced method for fishpond detection. We compared the results of each improvement strategy to known ground truthing fishponds as the metric of success. For machine learning classifiers, we compared the precision, recall, and F1 score to determine the quality of results. Among four machine learning methods studied here, the classification and regression trees performed the best with a precision of 0.738, recall of 0.827, and F1 score of 0.780. Overall, the proposed strategies enhanced fishpond area detection in all districts within the study area.

(2) Combined remote sensing, machine learning, and farm survey summary results

We used machine learning techniques to extract information from freely available satellite images and estimate the area of waterbodies used for aquaculture in seven districts in southern Bangladesh, one of country's most important aquaculture zones producing fish for domestic markets and crustaceans for export. We combined machine learning derived estimates of aquaculture farm area per district with data from statistically representative farm surveys to estimate farm size, productivity, and total output, economic value of production, on-farm employment generation by gender, and demand for formulated and non-formulated feeds. Machine learning estimates returned a total farm area similar to that reported in Department of Fisheries (DOF) statistics, but we estimate that production of crustaceans (shrimp + freshwater prawn production) is 31% lower than officially reported by DOF in 2020, while fish production and total aquaculture production (fish + crustaceans) are 41% and 27% higher,

respectively. Aquaculture makes a massive contribution to food production, farmer incomes and employment in southern Bangladesh. We estimate that there were more than 500,000 farms in 2020, producing 787,000 t of aquatic food (89% fish and 11% crustaceans), with a mean yield of 3.1 t/ha. This production was worth a total $1.45 billion (farmgate value) and generated farm profits of $0.67 billion, after subtracting production costs (Table 1). These farms support 430,000 fulltime equivalent (FTE) jobs on-farm, of which 15% worked by women, and created demand for 759,000 t of feed, of which 30% comprised of formulated pelleted feeds. Our findings reveal great potential to combine remote sensing and machine learning techniques with representative surveys to estimate a range of statistics that are difficult to obtain otherwise, with potential to expand the approach to whole of Bangladesh and other countries

Figure 1: Economic and nutrient productivity by IAA system (USD/ha & AE/ha)



(1) Nutrient productivity estimation summary results

Farm productivity is usually measured in terms of biomass or income produced per area of land. Here, we extend the concept of productivity to measure production of energy (kcals) and micronutrients, and explore the relationship between the economic and nutritional productivity for 12 distinct types of Integrated Aquaculture-Agriculture (IAA) system, identified from a survey of 721 farms in Southwest Bangladesh. Nutrient productivity is expressed as the number of adults able to meet their total recommended annual intakes of selected nutrients from the food produced

on one hectare of land (AEs/ha). We estimated productivity of energy (kcal), iron, zinc, and Vitamin A under different IAA systems (see Figure 1, above). Farms integrated with fruits and vegetables, and farms producing fish with freshwater prawn tend to have higher economic productivity than non-integrated farms, and those producing fish only. Farms integrated with rice have higher energy productivity. Farms integrated with fruit and vegetables produce slightly more vitamin A. Ordinary least squares regressions confirm that, in general, integrated farms produce more nutrients per hectare than non-integrated farms. Vegetable production is a key driver of both economic and nutrient productivity. These findings have important implications for the design of Nutrition Sensitive Agriculture programs that can enhance the contributions aquaculture makes to nutrition security in Bangladesh and other countries.

(2) Feed trader value chain segment survey summary results

The rapid growth of aquaculture in Bangladesh over the past 3 decades has been facilitated by the increasing use of supplementary feed and increasing number of feed traders, but little is known about the organization and behavior of the trader segment of aquaculture value chain. We conducted a comprehensive survey with 79 feed traders (dealer, n=34; retailer, n=45) in seven districts of southern Bangladesh between May and August 2021 to address this knowledge gap. The main findings are as follows. (1) The volume of traded feed almost doubled and the number of traders increased more than 1.69 times over the past 10 years. (2) The average quantity of feed traded was 165 t/year, and significantly higher ($p \leq 0.05$) for dealers (310 t/year) than retailers (97 t/year). (3) The share of formulated feed in total feed traded was, 52% and differed between dealers (70% of total feed) and retailers (24% of total feed). The growth of floating feed sales was faster than that of sinking feed and non-pelleted feed. (4) Feed trading created an average of 13 days of employment per ton of feed across trader types, amounting to a total 1108 full time equivalent (FTE) jobs of which 59% family labor and 41% hired. (5) Almost all traders (93%) stored feed on wooden or bamboo platforms, maintained adequate storage facilities and sold feeds quickly (average turnover time 11 days), indicating efficient handling practices. (6) Formulated feed produced by 35 feed companies was traded, among which eight accounted for 74% of total formulated feed sales, indicating a diverse fish feed market in Bangladesh. (7) None of the traders reported experiencing any waste or loss of feed during the most recent completed customer transaction, and only 5% of traders reported a small portion of feed (1.7%) wasted or lost during transport from feed suppliers to traders' shops. (8) The average profit margin was 6.2% which are relatively modest, indicating that profits earned by feed traders are not exploitative. In sum, these findings suggest that the feed supply segment of the aquaculture value chain in Southern Bangladesh is dynamic, well-developed, and relatively competitive and efficient. This finding is contrary to the conventional wisdom, which often portrays the sector as inefficient and beset by problems.

(3) Feed trader value chain segment survey summary results

The rapid growth of aquaculture in Bangladesh over the past 30 years has been facilitated by the proliferation of fish traders and retailers, but comparatively little is known about the organization and behavior of actors in these segments of the aquaculture value chain in Bangladesh. We conducted a comprehensive statistically representative study with 329 aquatic product traders (wholesaler, n=50; auctioneer, n=75; depot, n=62; assembler, n=42 and retailer, n=100) in 31 markets from seven districts in south and southwest Bangladesh between January and May 2021 to address this knowledge gap. The total number of traders in surveyed markets increased by more than 175% within the past 10 years. Numbers of wholesalers grew faster than any other category of traders. Wholesalers trade the largest average volumes among the five actor types (526 t/year), of which 88% is fish. This finding is consistent with results from farm surveys conducted simultaneously in the same zone which show a

big increase in fish production over this period. Trading businesses are predominantly family owned and operated, and mainly create employment opportunities for men (99%). Fish trading created an average of 14 days of employment per ton of fish across all trader types, amounting to a total 2,542 full time equivalent (FTE) jobs created by traders in our sample of which 51% family labor and 49% hired. Trader's annual working capital requirements, operating costs and gross margins are substantial, averaging $18,630, $17,000, and $22,722, respectively across all trader types. Average marketing margins earned on each transaction average 6.0% of the sales value, ranging from 2.9% for auctioneers, to 14% for retailers. These are relatively modest margins, indicating that the rate of profit extracted by traders is not excessive.

Outputs and Conclusions

The project has been extremely productive in terms of the number and diversity of outputs generated to date these include the following:

- Thirteen short extension videos featuring farmers talking about innovative practices and adaptations in their own words.
- A dedicated project 'Aquaculture TV' Facebook page and YouTube channel.
- One online remote sensing and machine learning training course with six instructional videos.
- An online interactive decision making tool for visualizing survey results, hosted on the Michigan State University server.
- Three presentations in the FIL session at the World Aquaculture 2022 conference, Singapore.
- One Agrilinks blog.
- Two FIL success stories.
- A WorldFish project website collating all published materials.
- Two papers on remote sensing and machine learning methods already published in leading remote sensing field journals. A further three papers are the in final draft stages, for submission in December 2022 or January 2023. Four papers are under development, and planned for submission in 2023.

More details and links can be found in the section below on dissemination of scientific results. In conclusion, the project was highly effective in delivering multiple policy and capacity building oriented research outputs, under extremely difficult circumstances during the COVID-19 pandemic, thanks to excellent teamwork. The project introduced multiple innovative methodologies and approaches that can be adapted for use in other contexts and locations by future projects, and generated significant interest and proactive support from Bangladesh DOF. Future efforts could work to scale out these approaches to other countries, and mainstream them within Bangladesh

Technologies/Innovations developed, and what phase was achieved

Innovation 1

The project developed a publicly accessible interactive online data visualization tool combining information from remotely sensed images and surveys to estimate aquaculture's multi-dimensional contributions to the economy of Southwest Bangladesh, focusing on production, economic value-added, and employment – all differentiated by gender and value chain segment. This decision support tool was designed based on stakeholder consultations to facilitate user interaction with and visualization of the data generated and assist planning. To achieve this objective, the team developed a sophisticated algorithm for detecting waterbodies used for aquaculture in Southern Bangladesh. This region proved to be a particularly challenging environment for developing the analytical tool, because of the high diversity of water bodies (some permanent, some seasonal, some integrated with rice and other crops, many very small, or with narrow boundaries, or irregularly shaped). We had to expand ground-truthing to cover >1800 individual water bodies and seek higher resolution satellite images than freely available through Google Earth Engine, incorporate radar based satellite data, and adapt the algorithms used to adjust estimates for under-reporting of water body area due to use of low resolution satellite images. This resulted in development of a highly sophisticated aquaculture waterbody identification tool. The innovation has reached Stage 3: Proof of Concept

Innovation 2

The project established a dedicated Bangla language YouTube and Facebook channel to disseminate short videos featuring innovative individuals discussing their practices in their own words widely through social media channels for building capacity to adopt new technologies and speed up the uptake of improved practices among farmers and other value chain actors. In doing so, the project team successfully learned how to produce short films for the dissemination of messages about innovative practices among farmers and other aquaculture value chain actors. This was a steep learning curve, but the project team rapidly learned a range of new techniques needed to produce attractive information products. Some of the extension videos prominently feature women actors in the aquaculture value chain in Southern Bangladesh talking about their experiences and innovative practices in their own words, to serve as a source of information and inspiration for others. The innovation has reached Stage 3: Proof of Concept

Key Beneficiaries

The project had four main sets of beneficiaries

1) A total 146 participants in 3 project outreach workshops held in Bangladesh on August 4, 6 and 8, of which 10 women, 136 men, to whom project research findings and policy recommendations were presented, and who participated actively in discussions about their implications for collection of data on aquaculture statistics and policy support needs.

2) Viewers of thirteen short extension videos featuring farmers talking about innovative practices and adaptations in their own words disseminated via dedicated “Aquaculture TV” YouTube and Facebook pages. These videos received a total of 6420 views and other interactions during the project duration.

3) 136 participants in a six-part online interactive remote sensing and machine learning training course, based on instructional videos with live feedback sessions, of which 106 male, 30 female, 92 from Bangladesh, and 44 international.

4) 1 Bangladeshi national PhD student, registered at Bangladesh Agricultural University with co-supervision from the project international and host-country PIs.

How the scientific results were disseminated

Scientific results were disseminated in the following ways:

1) Policy outreach workshops
The project organized three end of project policy outreach workshops in Bangladesh:

- Final project outreach workshop hosted by Department of Fisheries in Dhaka on 2022-08-04. Seven presentations of survey findings and policy recommendations given. 64 Participants, of which 4 women, 3 youth, 33 senior DOF staff. The event was officially hosted and endorsed by DOF at in the main conference room at DOF headquarters in Dhaka.
- Project outreach workshop held at Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gopalganj on 2022-08-06. Six presentations given. 45 participants, of which 4 women, 4 youth.
- Project outreach workshop held at City Inn Hotel, Khulna on 2022-08-08. Six presentations given. 37 participants, of which 2 women, 3 youth.

2) Short online extension videos
Thirteen short extension videos featuring farmers talking about innovative practices and adaptations in their own words disseminated via dedicated “Aquaculture TV” YouTube and Facebook pages. These reached a total of 10,107 people (see Annex 1 for details)

3) Media coverage
The project outreach activities received substantial coverage in the Bangladesh national and regional press, with coverage in a total of 22 articles or reports (see Annex 2 for details)

4) Online six-part interactive remote sensing and machine learning training course with instructional videos

Online interactive decision management tool hosted by Michigan State University.

https://dsiweb.cse.msu.edu/demo/Bangladesh_aquaculture_data_portal_seven_districts/
https://dsiweb.cse.msu.edu/demo/Bangladesh_aquaculture_data_portal_all_districts/

5) Scientific papers

Two papers published in leading remote sensing field journals in 2021 and 2022:

- Hernandez-Suarez, J.S., Nejadhashemi, A.P., Ferriby, H., Moore, N., Belton, B., Haque, M.M. 2022. Performance of Sentinel-1 and 2 imagery in detecting aquaculture waterbodies in Bangladesh. *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2022.105534

- Ferriby, H., Nejadhashemi, A.P., Hernandez-Suarez, J.S., Moore, N., Kpodo, J., Kropp, I., Eeswaran, R., Belton, B., Haque, MM. 2021. Harnessing Machine Learning Techniques for Mapping Aquaculture Waterbodies in Bangladesh. Remote Sensing. 13: 4890. https://doi.org/10.3390/ rs13234890

Three papers in final draft stages, for submission December 2022:

- Ali, H., Belton, B., Haque, M.M., Jahan, K.M., Hernandez, R. In prep. The structure, conduct, and performance of the "hidden middle" of the aquaculture value chain in Bangladesh. For submission to *Food Policy*

- Ali, H., Belton, B., Haque, M.M., Jahan, K.M. In prep. The structure, conduct, and performance of the feed trader segment of the aquaculture value chain in Bangladesh. For submission to *Aquaculture*

- Ignowski, L., Belton, B., Ali, B., Thilsted, S.H. In prep Measuring Micronutrient Productivity of Integrated Aquatic Farming Systems for Nutrition-sensitive Food systems. For submission to *Proceedings of the National Academy of Sciences*

Four papers planned for submission in 2023

- Ali, H., Belton, B., Haque, M.M., Jahan, K.M. In prep. The structure, conduct, and performance of the farm segment of the aquaculture value chain in Bangladesh. For submission to *Aquaculture.*

- Ali, H., Belton, B., Haque, M.M., Jahan, K.M. In prep. The structure, conduct, and performance of the hatchery segment of the aquaculture value chain in Bangladesh. For submission to *Frontiers in Aquaculture.*

- Abaidoo, E., Belton, B., Reardon, T. In prep. Testing the relationship between allocative efficiency and resilience in aquaculture in Bangladesh. For submission to *American Journal of Agricultural Economics*

- Belton, B., Ali, H., Haque, M.M., Nejadhashemi, A.P., Ferriby, H., Hernandez-Suarez, J.S., Moore, N., Hernandez, R., Jahan, K.M. In prep. Harnessing machine learning to estimate aquaculture's contributions to the economy of southern Bangladesh. For submission to *Nature Food.*

6) Conference presentations

Three presentations in the Fish Innovation Lab session at the World Aquaculture 2022 conference, Singapore.

- Ignowski, L. Productivity of micronutrients from integrated aquaculture-agriculture systems: Evidence from Bangladesh. Presentation at World Aquaculture Society, Singapore, December 1, 2022
- Ali, H., Belton, B., Khondker, M., Hernandez, R. A., & Haque, M. M. The structure, conduct, and performance of the midstream segments of the aquaculture value chain in Bangladesh. Presentation at World Aquaculture Society, Singapore December 1, 2022
- Belton, B., Haque, M. M., Ali, H., Nejadhashemi, A. P., Hernandez, R. A., Khondker, M., & Ferriby, H. Harnessing machine learning to estimate aquaculture's contributions to the economy of Southwest Bangladesh. Presentation at World Aquaculture Society, Singapore December 1, 2022

These presentations will be presented at the Fish Innovation lab session at the Aquaculture America 2023 conference New Orleans in February 2023.

7) One Agrilinks blog and two success stories

- Zseleczky, L. 2021. Emerging Technologies Improve Aquaculture Data Systems in Bangladesh
- Haque M.M. and Belton, B. 2020. Shrimp Farming and Research in Bangladesh Adapts to COVID-19 Pandemic
- Haque M.M. and Belton, B. 2022. Machine learning tool paving the way to modernize aquaculture statistics in Bangladesh

8) Project website collating all materials: https://www.worldfishcenter.org/project/harnessing-machine-learning-estimate-aquaculture-production-and-value-chain-performance-0

Appendices

Annex 1: Summary of extension videos produced and promoted on Facebook and YouTube

Title of the video	Web link	# of views	# of people reached	# of likes	# of shares	# of comments
Facebook channel – Aquaculture TV https://www.facebook.com/aquaculturebau						
Farmer's Narrative: Making of shrimp harvesting trap	https://fb.watch/fJnRApZ2IU/	299	593	20	2	0
Farmer's Narrative: Pocket nursing for shrimp farms	https://fb.watch/fJnXH-JkKB/	106	328	14	1	1
Farmer's Narrative: Integrated rice-shrimp cultivation in a saline area	https://fb.watch/fJo21RAwZf/	117	396	13	3	1
Farmer's Narrative: Local nursing and selling of tiger shrimp post-larvae	https://fb.watch/fJo6R4m1os/	149	515	19	2	0
Farmer's Narrative: The negative impacts of climate change on prawn farming	https://fb.watch/dsmZ9XaD4h/	690	1500	130	18	104
Farmer's Narrative: Low-cost long distance irrigation	https://fb.watch/dsm_SAy48w/	227	693	39	7	9
Farmer's Narrative: Removing sludge from prawn/shrimp farm	https://fb.watch/dsn0cpd2s6/	666	1615	37	9	12
Farmer's Narrative: Women employment in integrated Gher farming	https://fb.watch/dsn1wTix2Q/	144	540	33	6	9
Farmer's Narrative: Maximum land utilization in integrated rice-prawn/fish-vegetable farm	https://fb.watch/dsn2Rrx0zh/	113	395	27	7	8
Farmer's Narrative: Seasonal Activities in Integrated Farming	https://fb.watch/dsn4kF_q03/	1100	3532	43	13	18
YouTube Channel- https://www.youtube.com/channel/UCUAZzkCXM_c2FaiJsqFjLGQ						
Farmer's Narrative: Integrated Rice-Prawn/Shrimp-Vegetable Farming System	https://www.youtube.com/watch?v=14yDwHhCsoU&t=11s	2050	-	38	-	13
Farmer's Narrative: Youth Employment in Aquaculture Value Chain (Wholesale Market)	https://www.youtube.com/watch?v=Z5H5eGRlHCo&t=6s	428	-	9	-	4
Farmer's Narrative: Women's Employment in the Aquaculture Value Chain	https://www.youtube.com/watch?v=_i07JyhrEEI&t=170s	331	-	8	-	3

Total		6420	10107	430	68	182

Annex 2: Links to articles on the project closing workshops published in the Bangladesh media

Dhaka

1. http://www.kholakagojbd.com/education/104957?fbclid=IwAR1Q6uAKWnQqsdOoAfexURzNPbvwbeuq4cNUTTHEUWmE9KXyJjz71H6tfK82.
2. https://www.channel24bd.tv/education/article/115413/%E0%A6%AE%E0%A7%8E%E0%A6%B8%E0%A7%8D%E0%A6%AF-%E0%A6%9C%E0%A6%B0%E0%A6%BF%E0%A6%AA%E0%A7%87-%E0%A6%AE%E0%A7%87%E0%A6%B6%E0%A6%BF%E0%A6%A8-%E0%A6%B2%E0%A6%BE%E0%A6%B0%E0%A7%8D%E0%A6%A8%E0%A6%BF%E0%A6%82-%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%AF%E0%A7%81%E0%A6%95%E0%A7%8D%E0%A6%A4%E0%A6%BF%E0%A6%B0-%E0%A6%AC%E0%A7%8D%E0%A6%AF%E0%A6%AC%E0%A6%B9%E0%A6%BE%E0%A6%B0?fbclid=IwAR3ru9cT8_HrA2y8maMv6VZ6uVtZfK8iUv2FeXjc7GUSuVZaoiCC9dKDlyI
3. https://www.protidinersangbad.com/education-premises/344739
4. https://www.jagonews24.com/m/campus/news/783260?fbclid=IwAR0G8BTxENCGUUexTkpFY5KDUD1JYiZO0MRto0u8CFWf7ID9PcMaBRU8v9o
5. https://bartabazar.com/archives/418983?fbclid=IwAR3KFRRrnTOfO8waCbFDmu511YM6eHuvPBLA79CV-O1vvJg00FEOLhJEknE
6. https://www.bahannonews.com/details/article/10041117/%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%A5%E0%A6%AE%E0%A6%AC%E0%A6%BE%E0%A6%B0%E0%A7%87%E0%A6%B0-%E0%A6%AE%E0%A6%A4%E0%A7%8B-%E0%A6%AE%E0%A7%8E%E0%A6%B8%E0%A7%8D%E0%A6%AF-%E0%A6%9C%E0%A6%B0%E0%A6%BF%E0%A6%AA%E0%A7%87-%E0%A6%AE%E0%A7%87%E0%A6%B6%E0%A6%BF%E0%A6%A8-%E0%A6%B2%E0%A6%BE%E0%A6%B0%E0%A7%8D%E0%A6%A8%E0%A6%BF%E0%A6%82-%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%AF%E0%A7%81%E0%A6%95%E0%A7%8D%E0%A6%A4%E0%A6%BF%E0%A6%B0-%E0%A6%AC%E0%A7%8D%E0%A6%AF%E0%A6%AC%E0%A6%B9%E0%A6%BE%E0%A6%B0/?fbclid=IwAR0b79o9XSZf-e6318Xp9OipOBebS2CYtU-dVSGbchIwICl0_yL468c7--E
7. https://www.agaminews.com/happy-news/news/83359

8. http://agrilife24.com/2021/2018-03-19-12-26-20/7603-l4ag11.html
9. https://agriview24.com/%E0%A6%AC%E0%A6%BE%E0%A6%95%E0%A7%83%E0%A6%AC%E0%A6%BF%E0%A6%B0-%E0%A6%97%E0%A6%AC%E0%A7%87%E0%A6%B7%E0%A6%95%E0%A6%A6%E0%A7%87%E0%A6%B0-%E0%A6%97%E0%A6%AC%E0%A7%87%E0%A6%B7%E0%A6%A3%E0%A6%BE/
10. https://khoborprotidin24.com/news/dese-prthmbarer-mto-mttsz-jripe-mesin-larning-przuktir-bzbhar
11. https://khoborprotidin24.com/news/dese-prthmbarer-mto-mttsz-jripe-mesin-larning-przuktir-bzbhar
12. https://agriview24.com/%E0%A6%96%E0%A7%81%E0%A6%B2%E0%A6%A8%E0%A6%BE%E0%A7%9F-%E0%A6%AE%E0%A7%8E%E0%A6%B8%E0%A7%8D%E0%A6%AF-%E0%A6%9C%E0%A6%B0%E0%A6%BF%E0%A6%AA%E0%A7%87-%E0%A6%AE%E0%A7%87%E0%A6%B6%E0%A6%BF%E0%A6%A8/
13. https://bangladesh.postsen.com/news/38852/Use-of-Learning-Technologies-in-Fisheries-Surveys.html
14. https://www.newagebd.net/article/177674/bau-holds-workshop-on-aquaculture-in-dhaka
15. https://thedailynewnation.com/news/330268/BAU-researchers-use-machine-learning-technology-in-fisheries-survey

Gopalganj

1. https://www.daily-sun.com/post/636407/Harnessing-machine-learning-workshop-held-at-BSMRSTU
2. https://www.channel24bd.tv/channel24-campus/article/115782/%E0%A6%AC%E0%A6%B6%E0%A7%87%E0%A6%AE%E0%A7%81%E0%A6%B0%E0%A6%AC%E0%A6%BF%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%AC%E0%A6%BF%E0%A6%A4%E0%A7%87-%E0%A6%AC%E0%A6%BE%E0%A6%95%E0%A7%83%E0%A6%AC%E0%A6%BF%E0%A6%B0-%E0%A6%AA%E0%A7%83%E0%A6%B7%E0%A7%8D%E0%A6%A0%E0%A6%AA%E0%A7%8B%E0%A6%B7%E0%A6%95%E0%A6%A4%E0%A6%BE%E0%A7%9F-%E0%A6%93%E0%A7%9F%E0%A6%BE%E0%A6%B0%E0%A7%8D%E0%A6%95%E0%A6%B6%E0%A6%AA-%E0%A6%85%E0%A6%A8%E0%A7%81%E0%A6%B7%E0%A7%8D%E0%A6%A0%E0%A6%BF%E0%A6%A4%C2%A0
3. https://www.jaijaidinbd.com/education/281376
4. https://www.protidinersangbad.com/education-premises/345273/%E0%A6%AC%E0%A6%B6%E0%A7%87%E0%A6%AE%E0%A7%81%E0%A6%B0%E0%A6%AC%E0%A6%BF%E0%A6%AA%E0%A7%8D%E0%A6%B0%E0%A6%AC%E0%A6%BF%E0%A6%A4%E0%A7%87-%E0%A6%AE%E0%A7%8E%E0%A6%B8%E0%A7%8D%E0%A6%AF-%E0%A6%9A%E0%A6%BE%E0%A6%B7-

%E0%A6%AC%E0%A6%BF%E0%A6%B7%E0%A7%9F%E0%A6%95-%E0%A6%95%E0%A6%B0%E0%A7%8D%E0%A6%AE%E0%A6%B6%E0%A6%BE%E0%A6%B2%E0%A6%BE-%E0%A6%85%E0%A6%A8%E0%A7%81%E0%A6%B7%E0%A7%8D%E0%A6%A0%E0%A6%BF%E0%A6%A4

5. http://www.kholakagojbd.com/education/105155

Khulna

1. https://agrilife24.com/2021/2018-02-24-11-08-45/7617-kag8ag.html?fbclid=IwAR3hGjS-MhhfLFLMqTeENm4ZthZCA0WcjBODVLELNm3US0ZuW-UM1wr_LZU

2. https://agriview24.com/%e0%a6%96%e0%a7%81%e0%a6%b2%e0%a6%a8%e0%a6%be%e0%a7%9f-%e0%a6%ae%e0%a7%8e%e0%a6%b8%e0%a7%8d%e0%a6%af-%e0%a6%9c%e0%a6%b0%e0%a6%bf%e0%a6%aa%e0%a7%87-%e0%a6%ae%e0%a7%87%e0%a6%b6%e0%a6%bf%e0%a6%a8/?fbclid=IwAR0wb_-1koa23GaylSxjkr43-jGC-CjXkTeU5dsAFaJ3JZYJ22a2Dd_PnLQ