Aquaculture 519 (2020) 734759

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Optimizing feed automation: improving timer-feeders and on demand systems in semi-intensive pond culture of shrimp *Litopenaeus vannamei*

João Reis*, Romi Novriadi, Anneleen Swanepoel, Guo Jingping, Melanie Rhodes, D. Allen Davis

School of Fisheries, Aquaculture and Aquatic Sciences, Auburn University, AL 36849,

ABSTRACT

The continued success of shrimp farming will rely on improved feed management and reductions in labor costs. Shrimp are omnivorous, eating many small meals with limited stomach capacity for food storage. Hence, increased performance may be obtained by spreading feed through multiple meals. Initial work has demonstrated that moving from two feeding per day into multiple feeding systems increases growth rate and production. Further advances have been made with on-demand (satiation) feeding systems. The goal of this work was to continue the development of standard feeding protocol's (SFP) for automatic feeding systems to maximize growth rates in semi-intensive pond production of shrimp, *Litopenaeus vannamei*. For this work a 13-week pond production trial was performed in 16, 0.1 ha outdoors ponds, stocked at a 26 shrimp/m^2, and fed 1.5-mm 40% crude protein for the first four weeks, and 2.4-mm protein soy optimized feed (35% crude protein) for last nine weeks, both produced by Zeigler Inc. Four treatments including: three fixed feeding treatments of 130, 145 and 160% of a SFP (SFP + 30%, SFP + 45%, SFP + 60%, respectively) were offered using automatic timer-feeders, and a fourth treatment utilized on-demand AQ1 acoustic feeding system. No statistical differences were found between treatments for survival (ranging 75.2–81.4%) and FCR (ranging 0.96–1.11). In general, increased feed inputs resulted in higher production. The best response was with the AQ1 system which adjusted feed inputs in real time and ended up offered higher feed inputs resulting in larger shrimp and yields. Based on results of this work and previous trials, standard feeding protocols for automated systems can be developed but to date, automated feedback systems which operate in real time out perform the standardized practices.

1. Introduction

Shrimp are one of the most popular seafoods. In aquaculture, *Litopenaeus vannamei* is the preferred shrimp species due to its culture characteristics and consumer acceptance. The continued success of shrimp farming will rely on intensification, improved feed management and reductions in labor costs. The cost of the feed is one of the most important variable costs, source of nutrients and consequently biological waste in shrimp production (Tacon and Forster, 2003). Commercially available shrimp feeds are generally adequate (Quintero and Roy, 2010), but proper application is essential for maximum economic and environmental improvements in aquaculture farms (Chatvijitkul et al., 2017; Van et al., 2017).

Shrimp are omnivorous benthic animals (Cuzon et al., 2004; Dall et al., 1990; Varadharajan and Pushparajan, 2013) with limited capacity to store food inside their digestive tract which results in slower continued ingestion of small quantities of feed. Several studies have shown enhanced growth performance for shrimp culture with multiple feedings throughout the day (Carvalho and Nunes, 2006; Jescovitch et al., 2018; Ullman et al., 2019a). This is due to increasing the availability of feeds but also the time that feed is in contact with water which is accepted to reduce its nutritional value (Obaldo et al., 2002). Ullman et al. (2019c) reported reduced growth performance and higher FCR in shrimp feeds that were previously leeched for over 0.5 h before feeding. This confirms the hypothesis that the longer feed is in the water the lower the nutritional value hence indicating small quickly consumed meals are preferential. Multiple small and quickly consumed feedings may improve nutrient delivery through reduced nutrient leaching resulting in improved growth and waste management. Nevertheless, offering multiple meals can be very labour intensive and economically impracticable in regions such as the Americas where labour cost is high in comparison to South East Asia which tends to use more feedings per day (Davis et al., 2018).

Contrary to many fish species, shrimp feeding behaviour does not allow visual perception of feed intake. Moreover, adequate estimations of population size and biomass are essential for feed management (NRC, 2011) which is particularly complex in non-clear water systems such as ponds. Therefore, estimating or adjusting feed inputs to meet the intake demands of shrimp can be very challenging. Regardless, there are various strategies to manage feed inputs for shrimp production.

Quite often feed tables are used by farmers ((Casillas-Hernandez et al., 2006 #23), 2006) which are based on previous production cycle data and serve as a reference for future cycles regardless of feed delivery system. Feed trays are one of the most common feed management strategies for they allow gross estimation of feed intake (Martinez-

* Corresponding author.
E-mail address: Jzt0062@auburn.edu (J. Reis).

https://doi.org/10.1016/j.aquaculture.2019.734759
Received 20 May 2019; Received in revised form 19 November 2019; Accepted 19 November 2019
Available online 21 November 2019

Cordova et al., 1998). Nevertheless, being a very high labour-intensive technique is a major setback (Bador et al., 2013; Davis et al., 2018; Ullman et al., 2019a). As a response to the necessity of the shrimp farming industry to improve its feed management protocols, some techniques and technologies have risen to address this issue.

Timer feeders are not a recent technology and are extensively used in various sectors and aquaculture production systems. These feeders enable increasing the number of feedings without negatively impacting labor cost. Ullman et al. (2019a) has reported no significant improvements in production for ponds fed same increasing feed amount twice a day in contrast with ponds fed the same amount but fed six meals a day. This indicates that better productivity can be achieved by increasing both number of meals and feed inputs. In parallel, animal feeding activity is also an important tool in aquaculture. Simplest feeding feedback in fish is visual observation which will not work in shrimp ponds due to both the size of the animal and poor visibility in the water. Using a different approach, for the last decade on-demand acoustic feedback feeding systems have proven to be a reliable tool in shrimp farming (Silva et al., 2019). These feeding systems respond to the signature clicking noise produced by shrimp while feeding. Previous works by Napaumpaipom et al. (2013) in high density, intensive systems and Jescovitch et al. (2018), Ullman et al. (2019a, 2019b) in semi-intensive conditions have shown improvements in growth performance by application of acoustic demand-feeding system in comparison to hand-feeding and timer feeder techniques in semi-intensive systems. As a continuation, this study aims towards improving timer-feeder protocols by adjusting feed amount and compare it with acoustic demand-feeding systems.

2. Material and methods

This trial was performed at Alabama Department of Conservation and Natural Resources, Claude Peteet Mariculture Center, Gulf Shores, Alabama. Pacific white shrimp L. *vannamei* larvae (2.3 mg) were obtained from Shrimp Improvement Systems (Islamorada, FL, USA), acclimated and nursed in a greenhouse system for 18 days. Juvenile shrimp (6 mg) were then stocked in outdoor ponds at a density of 26 shrimp/m^2. The production research was carried out in 16, 0.1 ha outdoor ponds over a 13 wk. production period.

The ponds used through the growout period were approximately 0.1 ha in surface area (46 × 20 × 1.0 m) lined with 1.52 mm high-density polyethylene with a 25 cm layer of sandy-loam soil on the bottom. Ponds were filled with brackish water (10.8–12.9 g/l) from Intracoastal Canal between Mobile and Perdido Bay, Alabama, filtered through a 250 μm cloth mesh filter bag. Pond primary productivity was promoted by adding inorganic fertilizers (1687 ml of 32–0-0 and 303 ml 10–34-0 for 5.70 kg/ha of N and 1.03 kg/ha of P) to the ponds two weeks prior to stocking. The same fertilizing treatment was repeated for every pond one week after pond stocking as Secchi readings for all ponds was still approximate to the ponds total depth. To try to maintain dissolved oxygen (DO) above 3 mg/l, all ponds were supplied one 2-hp surface aerator (Aire-O_2, Aeration Industries International, Inc., Minneapolis, MN, USA) as the primary source of mechanical aeration and one 1-hp surface aerator (Aquarian, Air-O-Lator, Kansas City, MO, USA) for backup and/or additional aeration. No water exchange was done throughout this trial.

2.1. Feed management

All ponds were offered the same two diets: 1.5-mm commercial diet (40% crude protein, 9% crude lipids) produced by Zeigler Inc. (Gardners, PA, USA) for the first four weeks, and 2.4-mm protein soy optimized feed (35% crude protein, 8% crude lipids) produced by Zeigler Inc. from the fourth week on, according to the treatments. Diet formulation for this experiment was the same as used by Ullman et al. (2019a). For evaluation of the potential for automation the four treatments used were a standard feeding protocol (SFP) + 30%, SFP + 45%, SFP + 60% and a passive acoustic feeding system (SF200 Sound feeding system, AQ1 Systems, Tasmania, Australia). SFP was calculated based on an expected weight gain of 1.3 g/wk., a feed conversion ratio (FCR) of 1.2, and a weekly mortality of 1.5% during growout period. The SFP used in this experiment was based on Davis et al. (2006) which was developed to optimize growth and FCR when using two feedings per day, resulting in satisfactory results as reported by Sookying et al. (2011). It was also used as the reference for the development of a protocol for timer feeders with satisfactory results as well as reported by Sookying et al. (2011), Van et al. (2017), Jescovitch et al. (2018) and Ullman et al. (2019a, 2019b). Each of the four replicates for every treatment was randomly assigned to a pond except for the AQ1 system treatment due to electricity constraints. All feeders used for SFP treatments were BioFeeder (BioFeeder SA, Guayaquil, Ecuador) timer-feeders, feeding once every 20 min from 0700 to 1900. Biofeeder feed management (*e.g.* set feed amount, turn on/off) was done remotely using the feeder's specific software. AQ1 feeding system fed *ad libitum* using a hydrophone with computer software to monitor feeding activity. All ponds under AQ1 system management were also equipped with an underwater DO sensor (placed approximately 10 cm off the pond bottom) and the system was set to only allow feeding when DO levels were above 4 mg/l. In all four ponds under AQ1 system treatment the main aerator was connected to the system so it could control aerator activity based on information provided by DO sensor. All ponds were hand-fed a SFP-based amount twice a day for the first 30 days after which BioFeeders were initiated. AQ1 system was started on the 34th day of pond production.

2.2. Sampling and water quality

After 17 days of pond culture, shrimp were sampled weekly through the remaining production cycle using a cast net (1.52 m radius and 0.96 cm mesh) to collect approximately 60 individuals per pond. Pond sampling enabled weight recording for growth assessment and inspection for general health. Ponds were monitored (DO, temperature, salinity, and pH) at least three times a day, at sunrise (0500–0530 h), afternoon (1400–1430 h) and sunset (1900–2000 h), using a YSI ProPlus meter (Yellow Springs Instrument Co., Yellow Springs, OH, USA). Secchi disk readings were recorded once a week as total ammonia nitrogen (TAN) and chlorophyll *a* concentration were recorded twice a week. Water samples were taken in the morning at the surface and TAN was analysed with a high performance ammonia ion selective electrode (Thermo Fisher Scientific Inc., Waltham, MA, USA). Direct calibration of the electrode was conducted by preparing a serial dilution of a 100 +/− 1 mg/l ammonia standard (certified traceable to NIST standard reference material) to create three ammonia standards (0.1, 1.0 and 10.0 mg/l), calibration was performed prior to each week's analysis. Chlorophyll samples were taken once a week by filtering a water sample through glass fiber filters (47 mm diameter) using a vacuum pump. Filters were kept in plastic 35 mm film canisters and shipped to E.W Shell Fisheries Center at Auburn University. Analyses were performed according to standard analytical protocols for chlorophyll *a* by membrane filtration, acetone-methanol extraction of phytoplankton and spectroscopy (Eaton et al., 2005).

All AQ1 treatment ponds were provided a DO sensor with real-time oxygen information on those ponds. All sensors were cleaned twice daily to prevent fouling and misreading. Calibration was performed only once through the entire cycle. Due to equipment failure near the end of the cycle, one of the AQ1 treatment ponds had the DO sensor and automatic aeration disconnected and was fed *ad libitum* from 0700 to 1900.

2.3. Harvest and shrimp value

The ponds were harvested over three days at the end of the 13-week

culture period. Ponds were partially drained and the night before harvest the level was reduced to about one third and aeration was provided using the surface aerator. On the day of harvest, the remaining water was drained and the shrimp were pumped out of the catch basin using a hydraulic fish pump equipped with a 25 cm diameter suction pipe (Aqua-Life pump, Magic Valley Heli-arc and Manufacturing, Twin-Falls, Idaho, USA). The pump was placed in the catch basin and shrimp were pumped, de-watered, and collected into a hauling truck. Shrimp were then rinsed, weighed in bulk, and 150 were randomly selected to measure individual weights and determine the size distribution. A subsample of these shrimp were collected and frozen for subsequent analysis. Whole body proximate with minerals analysis of the shrimp was performed by Midwest Laboratories (Omaha, NE, USA).

Shrimp prices used were the three year average (2014–2016) as reported by Urner Barry (Urner Barry, Toms River, NJ, USA) for Latin American Farmed white shrimp, whole. The partial value was calculated by subtracting the feed costs from the production value as calculated from the Urner Barry prices and the size distribution of shrimp produced. The feed prices were $1.72/kg for the starter diet and $1.09/kg for the grower diet.

2.4. Statistical analysis

Statistical analysis of the growth data was conducted with SAS 9.4 (SAS Institute, Cary, NC, USA) to perform a one-way analysis of variance to determine significant difference (p-value < .05) among treatments, the assumptions for ANOVA were met. Student-Newman-Keuls multiple range test was used to determine differences among treatments. Effect of feed inputs in low DO occurrences was analysed through a regression analysis.

3. Results

During this trial, main water quality parameters were kept within typical range for shrimp production (Boyd and Tucker, 1992) (Table 1). To evaluate the effects of nutrient loading on oxygen demand. The occurrences of DO reading below 2.5 were summer across time. Figure1 shows the number of low DO occurrences for each pond identified by treatments. Regression analysis was conducted on the whole data set regressed against final feed input. Although feed inputs affect the ponds biological oxygen demand (BOD) and most occurrence were registered at dawn, there is no linear correlation (R^2 = 0.0944) (Fig. 1) between the number of low oxygen occurrences (< 2.5 mg/l) in DO readings and the feed input for each pond.

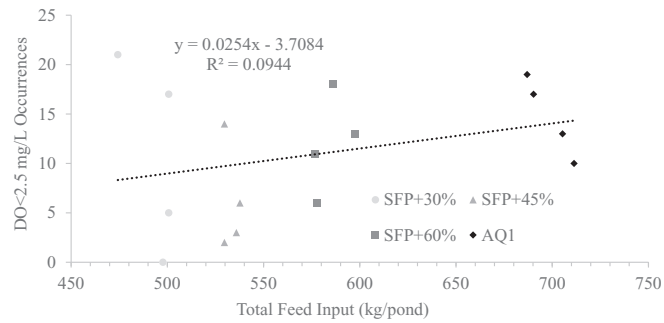

Fig. 1. Relationship between total low oxygen occurrences (< 2.5 mg/l) per treatment and total feed input.

Production data is summarized in Table 2 with final weights and yield generally following the level of feed input. The mean final individual weights of shrimp were significantly different between timer feeder treatments and AQ1 but not among timer feeder treatments. Weekly growth and yield were significantly different between the two treatments with lower feed inputs (SFP + 30% and SFP + 45%) and the highest feed input treatment (AQ1). Survival ranged between 72.5 and 81.4% and FCR between 0.96 and 1.11 but no statistical differences were found among these parameters. Figs. 3 and 4 present average treatments feed inputs and average individual weight throughout the production cycle. Feed inputs (kg/ha) were different among treatments, as shown in Table 2.

Results for feed input analysis are summarized in Fig. 4. Data summarized in Fig. 4 did not include data until day 17 due to lack of sampling although feed amount was adjusted on day 10 based on expected growth and survival. Combined analyses of data revealed increasing differences in size as previously indicated by Figs. 2 and 3.

Proximate whole body composition analysis are summarized in Table 3. SFP + 60% produced shrimp with significantly lower ash% than SFP + 45% but no other statistical differences were found in any of the other parameter evaluated in whole body composition analysis.

Feed costs and economic value of shrimp produced is summarized in Table 2. Significant differences were found for all treatments in both feed inputs and feed cost. However, for shrimp value and partial income statistical difference were only found between both SPF + 30% and SFP + 45% in comparison to AQ1 treatment.

Table 1
- Summary of water quality parameters for the four treatments over the 13 wk. culture period. Values are presented as mean ± standard deviation and maximum and minimum value are presented in parenthesis.

	SFP + 30%	SFP + 45%	SFP + 60%	AQ1
Morning DO[a] (mg/l)	3.81 ± 1.14 (1.65, 9.90)	3.95 ± 1.33 (0.82, 13.81)	3.66 ± 1.04 (1.77, 7.93)	3.66 ± 1.11 (0.78, 7.02)
Afternoon DO[a] (mg/l)	10.68 ± 2.78 (4.32, 18.05)	10.48 ± 2.81 (2.71, 21.36)	10.69 ± 2.73 (3.38, 16.97)	10.60 ± 2.99 (2.94, 10.02)
Night DO[a] (mg/l)	9.73 ± 2.70 (3.56, 18.5)	9.34 ± 2.97 (3.17, 24.11)	9.31 ± 2.69 (2.77, 16.89)	9.35 ± 3.04 (1.87, 18.36)
Temperature (°C)	31.8 ± 1.7 (27.4, 36.3)	31.7 ± 1.6 (27.5, 38.1)	31.6 ± 1.7 (24.6, 35.4)	31.4 ± 1.6 (27.3, 35.0)
pH	8.48 ± 0.79 (6.81, 10.01)	8.45 ± 0.75 (6.8, 9.81)	8.39 ± 0.76 (6.87, 9.87)	8.33 ± 0.70 (6.95, 10.18)
Salinity (g/l)	9.27 ± 1.35 (7.13, 12.09)	10.71 ± 2.58 (7.73, 11.41)	9.68 ± 1.42 (6.72, 12.36)	10.28 ± 1.25 (8.03, 12.88)
TAN[b] (mg/l)	0.4 ± 0.7 (< 0.001, 3.0)	0.5 ± 1.0 (< 0.001, 4.0)	0.6 ± 1.0 (< 0.001, 4.0)	0.7 ± 1.9 (< 0.0001, 6.0)
Chrolorophyll a (μg/l)	307 ± 213 (3.7, 990)	363 ± 202 (71, 745)	396 ± 325 (25, 1742)	318 ± 203 (35, 1044)

[a] DO - Dissolved Oxygen.
[b] TAN - Total Ammonia Nitrogen.

Table 2
- Summary of Pacific white shrimp response to different feed management protocols.

Treatment	IndW (g)	Survival	Weekly Growth (g)	Yield (kg/ha)	Total Feed Input (kg/ha)	FCR	Feed Cost ($/ha)	Shrimp Value ($/ha)	Partial Income ($/ha)
SFP + 30%	26.29[a]	77.6	1.97[a]	5226[a]	4933[a]	0.99	5592[a]	43,490[a]	37,898[a]
SFP + 45%	26.87[a]	75.2	2.04[a]	5115[a]	5332[b]	1.11	6026[b]	42,468[a]	36,442[a]
SFP + 60%	29.04[a]	80.7	2.21[ab]	6128[ab]	5844[c]	0.96	6585[c]	52,623[ab]	46,039[ab]
AQ1	32.53[b]	81.4	2.49[b]	6869[b]	6984[d]	1.02	7828[d]	60,723[b]	52,896[b]
P-value	0.0096	0.9083	0.0091	0.0274	< 0.0001	0.7313	< 0.0001	0.0073	0.0164
PSE	1.18	6.52	0.093	39.62	5.07	0.097	55.3	3362	3380

[1]PSE: Pooled Standard Error.

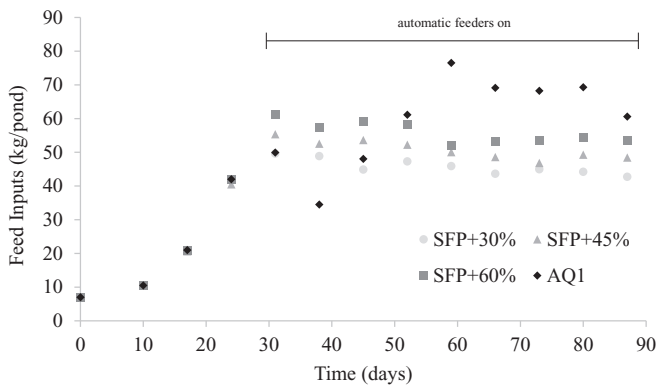

Fig. 2. Weekly feed inputs (kg/pond) through production cycle as average per treatment. Feed inputs were equivalent for the first 30–34 day. Timer feeders were initiated on day 30 and AQ1 feeders on day 34.

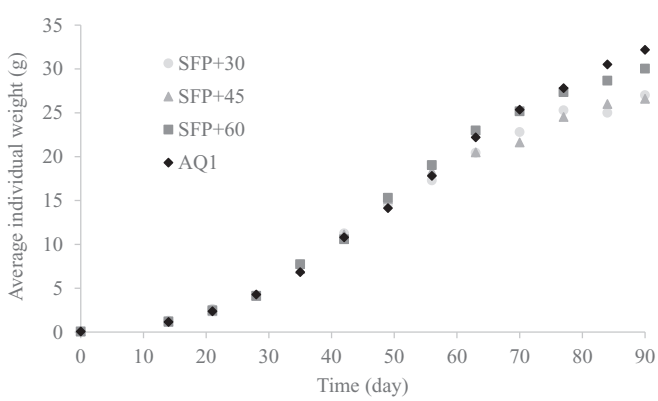

Fig. 3. Weekly average individual weight (g) as average per treatment.

4. Discussion

Commercial shrimp feeds are considered nutritionally appropriate and are one of the primary operating costs of most farms. To ensure the investment in high quality feed is maximized it is important to focus on feeding protocols Shrimp have been traditionally fed 2 to 4 meals a day either by hand-dispersion or through the use of feed trays. However, shrimp can be described as grazers in that they have evolved to find small patches of food with high frequency indicating that feed frequency is an important driver of nutrient intake. Ullman et al. (2019a) reported a significant increase in final weights of shrimp reared with 6 feeding/day as compared to those fed a similar amount of feed over two feedings per day. The use of automation to increase the number of feedings not only favors shrimp growth but also improves economic balance as labor requirement is reduced and feed efficiency is improved (Davis et al., 2018). Application of automatic feeders has shown many advantages in comparison with traditional methods. Within automatic feeders, on-demand acoustic feedback systems have shown improved performance over simpler timer-feeders (Jescovitch et al., 2018; Napaumpaipom et al., 2013; Ullman et al., 2019a, 2019b) and in some cased improved water quality has been reported.

During this entire production cycle water quality management aimed towards keeping dissolved oxygen levels above 3 mg/l. Given the variability between ponds as well as the variation in feed management it is difficult to make conclusions of the water quality data. Jescovitch et al. (2018) reported increased levels of TAN associated with increased feed inputs using the AQ1 system. However, our feed loading was considerably higher than the previously mentioned study yet there were minimal differences in water quality. The lack of differences across feed input levels would indicate that we were within the processing capacity of the pond based ecosystem. Under our conditions, aeration was managed either using automated set points AQ1 system or through manual management. Although managed we counted the days for which DO dropped below 2.5 mg/l. This data was plotted against feed inputs for each pond and presented in Fig. 1. This regression has a very weak fit (R^2 0.0944) and further statistical tests showed no significant

Table 3
Means of whole body composition for each treatment as analysed by Midwest Laboratories (Omaha, NE, USA).

Treatment	SFP + 30%	SFP + 45%	SFP + 60%	AQ1	*P*-value	PSE
Moisture %	74.9	75.0	75.2	74.1	0.5042	1.95
Dry Matter %	25.08	25.05	25.93	24.85	0.5042	1.95
Protein %	74.5	73.2	78.1	76.3	0.4336	8.79
Fat %	4.16	3.89	4.94	5.66	0.3793	2.75
Ash %	11.67[ab]	12.83[a]	10.29[b]	11.03[ab]	0.0250	2.06
Sulfur %	0.84	0.80	0.85	0.82	0.1278	0.04
Phosphorus %	1.62	1.61	1.43	1.57	0.2436	0.26
Potassium %	1.27	1.24	1.27	1.27	0.8351	0.09
Magnesium %	0.35	0.37	0.30	0.35	0.2459	0.09
Calcium %	3.62	4.10	3.09	3.69	0.3103	1.46
Sodium %	0.73	0.73	0.73	0.69	0.5147	0.08
Iron (ppm)	152.8	161.6	101.2	202.8	0.4222	173.41
Manganese (ppm)	7.6	7.1	3.6	6.6	0.3363	57.07
Copper (ppm)	137.5	136.0	125.8	136.8	0.0640	27.94
Zinc (ppm)	78.3	73.4	75.5	75.2	0.3439	6.18

differences between treatments ($p = .2469$) ultimately confirming that the ponds were able to process the nutrients load.

During the first 30 days feeding program for all treatments was preprogramed following the previously described SFP which assumes estimates for the population as well as growth. Although this is not an optimized protocol it is assumed that primary productivity is considerable portion of nutrient intake and that feed inputs must be systematically increased to allow conditioning of the pond to the high feed loads. Also, as shrimp feed lower in food chain ponds primary productivity is more than likely one of the main sources of nutrients at this stage and uneaten feed will trigger phytoplankton growth as well (NRC, 2011). After 30 days of culture, treatments were initiated and feed was dispersed using timer feeders. At day 34 the AQ1 system was initiated. Total feed inputs (kg/ha) were significantly different for every treatment (Table 2). By evaluating feed inputs through the production cycle (Fig. 2) and comparing this to the average individual growth (Fig. 3) it is possible to discern some feeding differences. Between days 38 and 45 there was a substantial reduction in feed input for AQ1 feeding system. There are two possible interpretations of this: the small size of shrimp producing a minimal acoustic signal resulting in low feed inputs or primary productivity remains a sufficient food source for shrimp within that size class. As there no differences in mean weights it would appear reduced feed inputs did not affect growth. From this point forward AQ1 feed inputs steadily increase up to day 59 where it peaked. From 50 days to the end of production, feed inputs were highest for the AQ1 treatments. Based on sample weight it is apparent that up to 45 days of culture the lowest level of feed input was acceptable. However, after this point SFP + 30% and SFP + 45% feed treatment resulted in smaller shrimp or a reduced growth rate. Shrimp fed using the SFP + 60% level maintained similar growth as the AQ1 system through day 73 after which it appeared that growth was reduced. This data leads us to believe it is possible to obtain high growth rate with lower feed inputs than AQ1 although at some point feed will become a limiting factor for growth. Regardless no differences in FCR among treatments were registered and reported values are more than acceptable throughout all treatments.

Shrimp are not sampled during the first week as representative samples are difficult to obtain with small shrimp in ponds. Hence, with the exception of the first few week of production the collected data can be used to develop a feed curve. To do this, final survivals are used to back calculate the estimated number of shrimp at any given time point and the percent body weight calculated. This data is presented in Fig. 4 which does not include data from the first 17 days of production. This data can then be used as a recommended feed rate for shrimp produced under similar conditions.

Combined analyses or data also suggest that shrimp adjusted growth

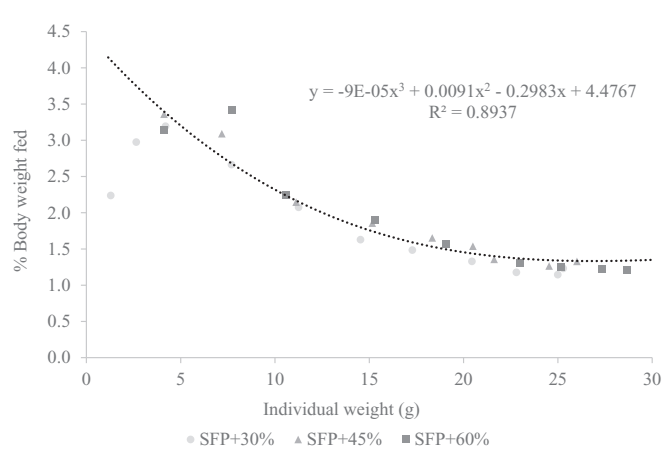

Fig. 4. Back calculated feed inputs expressed as percentage body weight for the various sizes of shrimp. Regression represents the results of pooled data.

based on the amount of food with higher feed inputs resulting in larger shrimp. Supporting this conclusion is the fact that ponds fed SFP + 60% also registered numerically higher average survival. Also, although feed inputs were only differentiated from day 30 on (Fig. 2), it is possible to identify larger individuals (Fig. 3) in SFP + 60% ponds at the same time as feed inputs by percentage body weight (Fig. 4) remain similar. This is likely a consequence of numerically higher survival (Table 2) in this treatment regardless of higher feed input and shrimp adjusting their growth to feed input as well. In short, combined analysis of data summarized in Figs. 3 and 4 indicates that shrimp are able to adjust their growth based on feed availability it also suggests that there may be a threshold for feed input over which relative growth does not increase. Consequently, from an economical and water quality management perspective our data suggests that shrimp could have been be fed SFP + 30% until individual sizes reach about 18 g (~day 50) and then feed inputs would be increased to SFP + 60% until the end of production. Possibly even further increase feed inputs for the last two weeks of production, as was seen in the AQ1 system, was responsible for further increased shrimp size (Table 2).

Feed management and nutrient composition of the diet is known to influence proximate composition of the animal albeit shrimp seem to be less responsive than other animals. To evaluate possible shifts in nutrient content, proximate analysis of whole shrimp body composition (Table 3) were determined. Significantly higher ash content of shrimp fed in SFP + 45% in comparison to SFP + 60%. Ullman et al. (2019b) has reported differences in several compounds between treatments, namely higher fat content for higher feed input treatments. However, in this research no differences were found in any components except for ash. In our work ash was significantly higher in shrimp reared on the SFP + 60% treatment as compared to those on the SFP + 60% feeding regime. Variation in ash content was not consistent across feed inputs; hence, it may simply be due to natural variation in the data or possibly small changes macro minerals such as Ca and P.

5. Conclusion

The results of this study underline the results achieved in similar studies by Jescovitch et al. (2018) and Ullman et al. (2019a, 2019b), indicating that higher production and value of L. *vannamei* produced in semi-intensive pond culture can be achieved through application of on-demand acoustic feedback systems. This study also shows that it is possible to establish an efficient feeding protocol for timer feeders. Therefore, reducing the performance differences between the two technologies. Nevertheless, efficient use of timer feeders heavily relies in adequate feeding plans based on previous production cycles as well as post feeding observations. Poor estimations of survival, growth and feed response are likely to negatively affect growth, environmental conditions (water quality) and financial performance.

For the intrinsic nature of a feedback technology is to feed on demand in real time, it is virtually impossible that any timer feeder will be as efficient as a real-time passive feedback system. However, our results confirm that a standard feeding protocol can be developed for automated feeding system that will support the enhanced growth rates seen when using these systems. Thus, providing guidance for this level of technology. Increased product value may also offset the installation and running cost of any of these technologies. However, as reported by Ullman et al., (2019a), it is not possible to accurately provide implementation costs due to a lack of linearity inherent to the facility and production setup.

Acknowledgements

The authors would like to express our gratitude to those who have reviewed this manuscript and the students and staff who participated in this project from Auburn University and Claude Peteet Mariculture Center. Special thanks to Zeigler Bros, Inc., BioFeeders and AQ1 for

support of the research. This research was supported by United Soybean Board Project #1810-353-0536 as well as the Hatch Funding Program of Alabama Agriculture Experiment Station. The mention of trademarks and proprietary products does not constitute endorsement by Auburn University and is not intended to exclude other products or services that may be suitable.

Declaration of Competing Interest

All authors of this research project would like to disclose the absence any personal or financial relationship with people or organizations that may inappropriately influence our work. This naturally includes all grant and sources of funding described in the paper.

References

Bador, R., Blyth, P., Dodd, R., 2013. Acoustic control improves feeding productivity at shrimp farms. Global Aquacul. Advocate 77–78.

Boyd, C.E., Tucker, C.S., 1992. Water Quality and Pond Soil Analyses for Aquaculture. Alabama Agricultural Experiment Station. Auburn University.

Carvalho, E.A., Nunes, A.J.J.A., 2006. Effects of feeding frequency on feed leaching loss and grow-out patterns of the white shrimp *Litopenaeus vannamei* fed under a diurnal feeding regime in pond enclosures. Aquaculture 252 (2–4), 494–502.

Casillas-Hernandez, R., Magallon-Barajas, F., Portillo-Clarck, G., Paez-Osuna, F., 2006. Nutrient mass balances in semi-intensive shrimp ponds from Sonora, Mexico using two feeding strategies: trays and mechanical dispersal. Aquaculture 258, 289–298.

Chatvijitkul, S., Boyd, C.E., Davis, D.A., McNevin, A.A., 2017. Embodied resources in fish and shrimp feeds. J. World Aquacult. Soc. 48, 7–19.

Cuzon, G., Gaxiola, G., Rosas, C., Guillaume, J., 2004. Nutrition of *Litopenaeus vannamei* reared in tanks and ponds. Aquaculture 235, 513–551.

Dall, W., Hill, J., Rothlisberg, P.C., Staples, D.J., 1990. The biology of Penaeidae. Advances in Marine Biology. Vol. 27 Academic Press, New York, NY.

Davis, D.A., Amaya, E., Venero, J., Zelaya, O., Rouse, D.B., 2006. A Case Study on Feed Management to Improving Production and Economic Returns for the Semi-Intensive Pond Production of *Litopenaeus vannamei*. Avances en Nutrición Acuícola VIII. Memorias del Octavo Simposio Internacional de Nutrición Acuícola. Universidad Autonoma de Nuevo Monterrey, Nuevo León, México, pp. 282–303 (970-694-333-5).

Davis, D.A., Ullman, C., Rhodes, M., Novriadi, R., Swanepoel, A., 2018. Automated Feeding Systems in Pond Production of Pacific White Shrimp. Global Aquaculture Advocate. https://www.aquaculturealliance.org/advocate/automated-feeding-systems-in-pond-production-of-pacific-white-shrimp/.

Eaton, A.D., Clesceri, L.S., Greenberg, A.E., Franson, 2005. Standard methods for the examination of water and wastewater. Washington, DC, USA: American Public Health Association, 21, 1600.

Jescovitch, L.N., Ullman, C., Rhodes, M., Davis, D.A., 2018. Effects of different feed management treatments on water quality for Pacific white shrimp *Litopenaeus vannamei*. Aquac. Res. 49, 526–531.

Martinez-Cordova, L.R., Porchas-Cornejo, M.A., Villarreal-Colemnares, H., Calderon-Perez, J.A., Naranjo-Paramo, J., 1998. Evaluation of three feeding strategies on the culture of white shrimp *Penaeus vannamei* Boone 1931 in low water exchange ponds. Aquac. Eng. 17, 21–28.

Napaumpaipom, T., Chuchird, N., Taparhudee, W., 2013. Study on the efficiency of three different feeding techniques in the culture of Pacific white shrimp (*Litopenaeus vannamei*). Kasetart Univers. Fis. Res. Bull 37 (2), 8–16.

NRC, 2011. Nutrient Requirements of Fish and Shrimp. National Academic Press, Washington D.C (376pp).

Obaldo, L.G., Divakaran, S., Tacon, A.G., 2002. Method for determining the physical stability of shrimp feed in water. Aquac. Res. 33 (5), 369–377.

Quintero, H., Roy, 2010. In: Alday-Sanz, V. (Ed.), Practical feed management in semi-Intensive systems for shrimp culture. The shrimp book. Nottingham University Press, Nottingham, UK, pp. 443–454.

Silva, J.F., Hamilton, S., Rocha, J.V., Borie, A., Travassos, P., Soares, R., Peixoto, S.J.A., 2019. Acoustic characterization of feeding activity of *Litopenaeus vannamei* in captivity. Aquaculture 501, 76–81.

Sookying, D., Silva, F.S.D., Davis, D.A., Hanson, T.R., 2011. Effects of stocking density on the performance of Pacific white shrimp *Litopenaeus vannamei* cultured under pond and outdoor tank conditions using a high soybean meal diet. Aquaculture 319, 232–239.

Tacon, A.G.J., Forster, I.P., 2003. Aquafeeds and the environment: policy implications. Aquaculture 226, 181–189.

Ullman, C., Rhodes, M., Hanson, T., Cline, D., Davis, D.A., 2019a. Effects of four different feeding techniques on the pond culture of Pacific white shrimp, *Litopenaeus vannamei*. J. World Aquacult. Soc. 50, 54–64.

Ullman, C., Rhodes, M.A., Davis, D.A., 2019b. Feed management and the use of automatic feeders in the pond production of Pacific white shrimp *Litopenaeus vannamei*. Aquaculture 498, 44–49.

Ullman, C., Rhodes, M., Davis, D.A., 2019c. The effects of feed leaching on the growth of Pacific white shrimp *Litopenaeus vannamei* in a green-water system. Aquac. Res. 50, 3074–3077.

Van, T.P.T.H., Rhodes, M.A., Zhou, Y., Davis, 2017. Feed management for Pacific white shrimp *Litopenaeus vannamei* under semi-intensive conditions in tanks and ponds. Aquac. Res. 48, 5346–5355.

Varadharajan, D., Pushparajan, N., 2013. Food and feeding habits of aquaculture candidate a potential crustacean Pacific white shrimp *Litopenaeus vannamei*. J Aquac Res Development 4, 1–5.