TOPIC AREA

CLIMATE CHANGE ADAPTATION: INDIGENOUS SPECIES DEVELOPMENT

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SUSTAINABLE SNAKEHEAD AQUACULTURE IN CAMBODIA

Climate Change Adaptation: Indigenous Species Development/Experiment/16IND01UC

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ABSTRACT

The Cambodian government banned snakehead aquaculture in 2004 due to unsustainable methods. Recent research in Vietnam led to sustainable practices there. As part of technology transfer to Cambodia, a study was conducted to compare survival and growth of domesticated snakehead from Vietnam (VN) with those of non-domesticated snakehead from Cambodia. Cambodian broodstock fish were collected from Mekong River (MR) and Tonle Sap (TS), and F1 Cambodian fish from previous breeding (F1) were also used. Larvae from spawns of four broodstocks (VN, MR, TS, and F1) were subjected to a weaning protocol developed in Vietnam in a 60-d hatchery phase, followed by a 6-month grow-out in ponds. VN fish grew significantly faster than Cambodian fish in the hatchery, followed by continued rapid growth in the grow-out phase, largely due to increased feed consumption. Cannibalism rates ranged from 40-42% in the hatchery phase except for MR fish (57%) and 12-45% (VN lowest, MR highest) in the grow-out phase. It is not known whether differences are due to inherent genetic differences between wild Vietnamese and Cambodian fish, or to selective breeding (intentional or not) in Vietnam. Results will inform Cambodian aquaculture policy following the lifting of the ban in 2016.

Also, an experiment was conducted in Vietnam to assess spawning of various broodstock types (domesticated male x domesticated female; wild male x wild female; wild male x domesticated female and domesticated male x wild female) and the subsequent survival and growth of their offspring. Domesticated broodstock were generally larger than wild broodstock. Fecundity, fertilization rate and hatching rate of wild x wild fish were higher than those for any of the other treatments. Egg diameter and larval length at hatch and at yolk absorption were also greater for the offspring of the wild x wild fish cross than for other treatments. Survival of fingerlings after 45 days was slightly higher for offspring of the domesticated x domesticated cross, but growth was greatest in the offspring of the wild male x domesticated female cross.

INTRODUCTION

In Cambodia wild snakehead were traditionally cultured in small cages and ponds prior to the snakehead aquaculture ban (see below). Feed represented more than 70% of the total operational cost and the main type of feed for wild snakehead culture was small-sized fish (SSF), representing 60 to 100% of the total feed used depending on feeding strategies adopted by different farmers. During the dry season (October to May), the most important source of feed was freshwater SSF, while more

marine SSF species were used during the rainy season (June to September). Importantly, the snakehead production contributed more than 70% of total aquaculture production in Cambodia due to its popularity as food. Snakehead still has high market and trade demand in Cambodia as well as in Viet Nam, being found in most Cambodian and Vietnamese dishes at all wealth class levels (i.e. poor, medium and rich people). During the first phase of AquaFish CRSP (2007-2009), the study revealed that 33 species of freshwater SSF in the Viet Nam Mekong Delta (Hien et al. 2015) and nearly 200 species of SSF in the Cambodia Mekong basin (So et al. 2009) were detected in the supply of SSF for snakehead culture in Vietnam and Cambodia, respectively, including juveniles of commercially important fish species. Overall, SSF contribute more than 70% to total freshwater capture fisheries production in Cambodia (So et al. 2009).

The government of Cambodia put a ban on snakehead farming in September 2004 by the Announcement No. 4004. After the ban on snakehead culture in Cambodia, snakeheads have illegally been imported from the neighboring countries, particularly from Vietnam, to supply high local market demands in Cambodia. Furthermore, freshwater SSF have illegally been exported to Vietnam for feeding the significantly and commercially developed snakehead aquaculture in Vietnam. The first phase study of AquaFish CRSP (2007-2009) indicated that the incentives for choosing snakehead over other fish species by tens of thousands of fish farmers are strong, as it generates more than 10 times higher profits than other fish species(So et al. 2009). Therefore, the ban not only resulted in positive impacts on poor consumer group's from increased availability of freshwater SSF in Cambodia, but also provided negative effects on food and nutrition security and livelihood of tens of thousands of snakehead farmers who depended on this livelihood for improving household food and nutrition security and generating household income. In other words, these snakehead fish farmers have lost their important livelihoods and household income. Moreover, the ban also does not provide positive impacts on snakehead wild stocks as fishing pressure on wild snakehead using illegal and destructive fishing gears, particularly electro-shockers, has increased in recent years in order to supply local and external markets. In order to remove this ban, the same announcement mentioned that successful technologies of domesticated breeding, weaning and rearing or growing-out of snakeheads using formulated diets should be developed and made applicable at on-station and on-farm levels in Cambodia.

During the second phase of AquaFish CRSP (2009-2011), wild striped snakehead *Channa striata* broodstocks were successfully developed, matured and semi-artificially induced to spawn using the hormone HCG on-station in Cambodia. The *C. striata* aged 30 days old after hatch could gradually and successful accept AquaFish CRSP Snakehead Formulated Feed developed by AquaFish CRSP project as replacement of SSF at the rate of 10% every three days for a period of 30 days of feeding; and during the third phase of AquaFish Innovation Lab (2013-2015), the wild snakehead larvae aged 17 day-old after hatch could gradually wean (using the protocol adopted from Hien and Bengtson 2009; 2011) and accept the formulated feed. These fish were grown from larvae to adult fish (as F1 generation) at FARDeC by feeding them with pelleted feed developed by the AquaFish CRSP project (Nen et al., 2015). F1 mature adult snakehead will be developed into F2, F3and F4 generations to optimize the growth and survival rate while feeding on formulated, pelleted feed to ensure the efficient production and economic benefit, in order to release the ban on snakehead aquaculture and to sustain this aquaculture industry in Cambodia without negatively affecting the wild SSF populations. As snakehead culture in Vietnam becomes more domesticated, there is concern about the possibility of inbreeding in hatchery broodstocks. A method is needed to try to minimize inbreeding. We conducted a breeding experiment at CTU between wild and domesticated snakehead collected in Vietnam. If the off-spring from this back-cross perform as well in hatchery conditions as the same domesticated parent, back-crossing could be a good strategy to reduce potential inbreeding resulting from long-term domestication.

This study contributes to the goal of the overall project, which is enhanced trade and investment for global fishery markets and improved nutrition and food security through sustainable aquaculture development in Cambodia, especially to overturn the ban on snakehead aquaculture in Cambodia. The government required research to develop a sustainable process to raise farmed snakehead without doing harm to the wild fishery on which so many people depend. There is a great potential for enhanced trade in snakehead fresh and processed forms and investment for snakehead in Cambodia after the ban is released. In addition, if the wild snakehead fishery is sustainably managed after releasing the ban, there is also good potential to increase the trade and marketing of fresh and processed forms of wild snakehead with other Mekong riparian countries such as Thailand, Lao PDR and Viet Nam, and other countries in Asia, Europe, America and Australia. As a result, household food security, nutrition and income of tens of thousands of snakehead farmers who depend on snakehead aquaculture in Cambodia will be improved through sustainable aquaculture development and aquatic resources management.

The objective of the study was to focus on optimization of the domestication and development of F1 into F2 snakehead in Cambodia as comparing to wild snakeheads collected from five different natural water bodies in Cambodia and domesticated-hatchery snakehead collected from Vietnam in regard to weaning and grow-out on formulated or pelleted feed. Furthermore, the assessment of economic efficiency during grow-out was also conducted to provide technical and policy recommendations for sustainable snakehead farming as well as lifting the snakehead ban in Cambodia.

OBJECTIVES

To continue the domestication and development of Cambodian snakehead *Channa striata* brooders, specifically:

- To compare growth performance and survival rate of different snakehead strains regarding to weaning and grow-out experiments; and
- To compare economic efficiency of grow-out experiments of the different snakehead strains.

MATERIALS AND METHODS IN VIETNAM:

Wild snakehead from U Minh Wetland (U Minh dist., Cam May province) were collected and conditioned in the hatchery in Cantho University, Vietnam. Domesticated snakehead were purchased from a hatchery in An Giang (Chau Phu dist., An Giang provice). They were trained via feeding with commercial pellet containing 40% crude protein for 2 months before breeding.

Induced spawning using HCG hormone

All snakehead broodstock fish were checked monthly for egg maturation based on the method of Nikolsky (1963). Broodstock with egg maturation at the same stage were selected for induced spawning in order to simultaneously produce batches of larvae for the weaning experiment. Male and female broodstock from wild and domesticated sources were stimulated with HCG and distributed randomly in fiber tanks (0.3 m3/tank). The cross breeding procedure is presented in Table 1. Each treatment was replicated with 10 pairs.

Weaning method

After yolk absorption at 3 days after hatching (dah), larvae from each treatment were fed with live *Moina* for 7 consecutive days till 10 dah, and then larvae were fed with a mixture of dead *Moina* and ground freshwater small-sized fish (replacing *Moina* by 20% per day) for 7 days more till 17 dah. Larvae were weaning onto formulated feed beginning at 17dah with replacement of small-size fish by 10% per day until freshwater small-sized fish werecompletely replaced by formulated feed. Formulated feed contained 40-50% crude protein (Hien et al., 2016 and Hien et al., 2017).

Statistical analysis
Significant differences ($p<0.05$) among the treatments in growth and survival rate and feed intake of snakehead larvae were determined by one- way ANOVA. Tukey's HSD test was used to determine specific differences among means where appropriate.

RESULTS IN VIETNAM:

Spawning results
The weight of wild strain fish (from U Minh wetland) varied from 0.3-0.6 kg/ind and domesticated strain (from farms in Chau Phu, An Giang) were 0.5-0.8 kg/ind. Spawning parameters are presented in Table 2.
Values of fecundity, fertilization rate and hatching rate of treatment 3 (Wild female x wild male) gave the highest results compared to other treatments, although the spawning rate was lower (Table 2). So the egg quality of wild snakehead are still better than with domesticated snakehead. Egg diameter in treatment 3 (Wild female x wild male) was higher than other treatments, along with the length of larvae at hatching and after yolk absorption (Table 3).

Larva rearing
After nursing 45 days, fingerling were collected to weigh and measure individually. The results are shown in Tables 4 and 5. Growth of larvae from crosses between wild males and domesticated females was better than that of other crosses. Survival of treatment 1 (domesticated female x domesticated male) gave the highest value (45.5%) compared to treatments 2, 3 and 4 at values of 41.3, 41.0 and 42.0%, respectively at $p<0.05$.

CONCLUSIONS

- After conditioning, snakehead breeders from wild and domesticated sources spawned with high rate (90-100%). Spawning parameters of wild snakehead source have high value.
- The survival rate of fingerlings from domesticated source is higher ($p<0.05$) than wild snakehead. However, the growth of fingerlings from wild female crossed with domesticated male is higher than that of other crosses.

MATERIALS AND METHODS IN CAMBODIA:

The experiment, consisting of weaning and grow-out phases, was conducted at the Freshwater Aquaculture Research and Development Center (FARDeC), Prey Veng province, Cambodia under the direct supervision of the Inland Fisheries Research and Development Institute (IFReDI). In addition to available breeders already at FARDeC (referred to here as F1, the offspring of Cambodian wild-caught fish), adult wild *C. striata* from different natural water bodies of Cambodia (Tonle Sap and Mekong River) were collected and conditioned for spawning at FARDeC. Domesticated snakehead were also purchased from a hatchery in Can Tho, Vietnam, and also conditioned at FARDeC for induced spawning to produce larvae for the experiment. Snakehead at that Vietnamese hatchery have been reared through severalgenerations, although there has not been a formal selective breeding program (T.T.T. Hien, personal communication).

All snakehead broodstock were checked monthly for egg maturation based on the method of Nikolsky (1963). Broodstock fish with egg maturation at the same stage were selected for induced spawning with HCG hormone in order to simultaneously produce batches of larvae for the weaning experiment. Those batches were used for weaning treatments to compare their growth performance and survival rate on pellet feed using the optimum weaning protocol for *C. striata* (So et al., 2011; Hien et al. 2017) from live *Moina sp.* to formulated feed, as follows.

After yolk absorption at 3 DAH, larvae were fed live *Moina* for 7 d till10 DAH, and then fed a mixture of dead *Moina* and ground SS fish (replacing *Moina* by 20%.day-1) for 7 d more till 17

DAH. The experiment began at 17DAH with replacement of SS fish by 10%.day-1 until SS fish were completely replaced by formulated feed made by Dr. T.T.T. Hien at Can Tho University, Vietnam for consistency with the diet used by Hien et al. (2017) and replicated by IFReDI and FARDeC research teams in Cambodia (So et al., 2011).

The experiment consisted of four treatments with six replicates each, with larvae originating from the four broodstock groups: F1 (broodstock were offspring of wild-caught Cambodian fish), Mekong (broodstock were wild-caught from the Mekong River in Cambodia), Tonle Sap (broodstock were wild-caught from the Tonle Sap in Cambodia), Vietnam (broodstock were purchased from a Vietnamese hatchery after several generations of domestication there). All treatments were subjected to the same weaning protocol, as mentioned above. Larvae were stocked in 100-L tanks with stocking density of 5 fish.L^{-1}. The fish were fed to satiation by hand twice daily. Any uneaten feed and feces were siphoned out before feeding.

Fish mortality, food consumption and water quality (temperature, pH and dissolved oxygen) were recorded daily. Larvae were sampled, weighed and measured at biweekly intervals. At the end of the weaning experiment, final wet body weight (FBW, mg), wet weight gain (WWG, mg) and survival rate were determined. Cannibalism rate was calculated from the number of fish stocked into each tank, minus number of known (i.e., removed) mortalities, minus number of fish remaining at the end of the experiment, divided by the number of fish stocked and multiplied by 100%.

Immediately following the weaning phase, fish from each treatment and replicate of that phase were transferred to corresponding treatments and replicates in ponds at FARDeC for the 6-month grow-out phase of the study. Each replicate was now contained in a 3 m x 1 m x 1.5 m hapa net. Fish were fed commercial pelleted feed (40% crude protein) to satiation by hand twice daily at 09:00h and 16:00 h. The amount of feed consumed by fish and fish mortality were recorded daily. Water qualities (temperature, pH, dissolved oxygen, NH_3 and NO_2) were monitored weekly. Fish growth was measured monthly with 30 sampled fish. The survival rate and cannibalism rate were determined at the end of experiment. At the end of the experimental grow-out phase, we also calculated the economic efficiency (profit) of the snakehead in different strains.

Data were subjected to analysis of variance, followed by Tukey's HSD test to determine treatment differences using SPSS 16.0 and differences were considered significant at $p<0.05$. *Data calculation*
SR (%) = (Numbers of fish at the end of experiment/ numbers of initial fish) x 100
WG (g) = Final body weight – Initial body weight
DWG (g fish-1 day-1) = (Final body weight- Initial body weight)/ number of experimental day
SGR (% of body weight day-1) = ((ln final weight — ln initial weight)/ number of culture day) x100
FI (g fish-1 day-1) = (Feed intake/no. fish)/ number of experimental day
FCR= Feed intake/ Weight gain
Profit (KHR; Khmer Riel) = Total income-total cost

RESULTS IN CAMBODIA

Hatchery phase

Snakehead larvae from the domesticated Vietnamese broodstock grew significantly more during the experiment than did larvae from any of the other three treatments, which did not differ among themselves (Figure 1a, Table 6). The greatest difference in growth between the Vietnamese fish and the Cambodian fish happened between days 40 and 60 of the experiment, although Vietnamese fish were already significantly larger than the Cambodian fish by day 40 (Figure 1a). The better growth of the Vietnamese fish appeared to stem primarily from greater feed intake (Figure 1b), but their FCR was not significantly different from that of the Tonle Sap or F1 fish; only the Mekong fish FCR was significantly higher (Table 6). Survival rate of Tonle Sap and F1 fish was significantly higher than

that of Mekong and Vietnamese fish (Table 6). Cannibalism was by far the largest cause of mortality and Mekong fish had a significantly higher cannibalism rate than did the other three treatments, which did not differ among themselves (Table 6).

Mortality from "natural causes" (i.e. fish found dead and removed from tanks during the experiment) was very rare.

Grow-out phase

Vietnamese fish continued their significantly greater growth in the grow-out phase, reaching a weight of about 340 g after 6 months, compared to weights of about 140-150 g for all the Cambodian treatment groups (Figure 2a, Table 6). Survival was highest for Vietnamese and F1 treatments, less so for the Tonle Sap treatment, and lowest for the Mekong Treatment, with cannibalism still contributing more to mortality than non-cannibalism causes (Table 6). FCR was not significantly different among treatments (Table 6), although feed intake of Vietnamese fish was significantly higher (Figure 2b). Yield.hapa^{-1} was significantly greater for the Vietnam fish than for any of the Cambodian fish (Table 6).

Economics

The economics of experimental snakehead is presented in Tables 7 and 8. In this experiment, since feed cost accounted for more than 70% of the total expenses, we focused only on feed cost (4200 KHR/kg) and income from selling snakehead on farm-gate price (8000 KHR/kg) in the current market to make the economic analysis. The Mekong strain showed lost profit (-1400 KHR/kg fish produced). The highest profit was attained in the Vietnamese domesticated strain (2000 KHR/kg fish produced), followed by Cambodian F1 domesticated strain and Tonle Sap strain (1600 KHR/kg fish and 300 KHR/kg fish, respectively).

DISCUSSION

To the best of our knowledge, this is the first demonstration of differences in weaning performance based on differences between larvae from wild-caught vs. domesticated broodstock. Fish from the Vietnamese broodstock appear to grow more (probably due to higher feed intake) while maintaining an acceptable FCR, although their cannibalism rate was the same as larvae of most of the wild-caught strains. This observation has multiple possible explanations. The most obvious is that domestication in Vietnam has produced a line of fish that have been selected over time (not necessarily intentionally by the hatchery managers) for greater feed consumption and growth. Given the high rates of cannibalism seen in all the treatments of our experiment, one can imagine that maximization of feed consumption and growth would be a trait for which selection occurs in a hatchery. Another explanation is that, even prior to domestication; wild fish in Vietnam were genetically different from those in Cambodia and could inherently grow faster, regardless of domestication. The finding that the fish in the F1 treatment in our experiment were similar to fish in the other treatments derived directly from Cambodian wild-caught fish suggests that any selection in the hatchery does not occur in just one generation. Finally, the observation that the cannibalism rate in domesticated fish from Vietnam was the same during weaning as that of fish from wild-caught Cambodian broodstock suggests that, even though selection for high-consuming, fast-growing fish may be a by-product of domestication, it apparently does not reduce the variance in growth rates among individuals that makes cannibalism possible.

Given the results of the weaning phase, it was not surprising that the Vietnamese fish would continue their rapid growth during the grow-out phase. Presumably, the same arguments made above for growth differences between Vietnamese and Cambodian fish apply to grow-out as well. Further examination of genetic differences would help elucidate the basis for growth differences. Selective breeding programs for increased growth have greatly benefitted the finfish aquaculture industry,

especially for Atlantic salmon (*Salmo salar* L. 1758), but for many other species as well (Gjedrem et al. 2012). Thus, domestication and breeding of Cambodian sources of *C. striata* may one day result in production similar to that seen for Vietnamese fish in these trials.

Based on research done in Vietnam to change aquaculture of *C. striata* from SS fish-based to pellet feed-based (Hien et al. 2015b, 2016) and technology transfer from Vietnamese to Cambodian scientists, the Cambodian government lifted the ban on snakehead in 2016. More research and policy development will be required before the Cambodian snakehead aquaculture industry achieves performance like that seen in Vietnam. Development of hatcheries, feed mills, and processing and distribution facilities are required for industry development. Results of the current study will help to inform further research and policy development to enable sustainable snakehead aquaculture in Cambodia.

CONCLUSIONS

The study concludes that both Viet Nam hatchery snakehead (domesticated) and Cambodia indigenous wild snakehead (non-domesticated) can accept formulated feed, with similar product quality. However, Vietnam hatchery snakehead show higher growth rate and profit than Cambodia wild capture snakehead and F1 generation because Vietnam hatchery snakehead has undergone domestication and selection breeding for more than 10 years. Considering economic efficiency, replacing freshwater small-sized by formulated feed up to 100% is possible for both Vietnamese domesticated snakehead and Cambodian domesticated snakehead, however, the domesticated snakehead shows higher profit than Cambodian domesticated snakehead.

Recommendations

The following recommendations should be carefully considered for policy and action plan development in order to achieve sustainable development snakehead aquaculture in Cambodia:

- The availability of good quality hatchery broodstock has very important implications for protecting the SSF that are usually fed to snakeheads.
- Sufficient numbers of broodstock should be developed at hatcheries through selective breeding and weaning techniques to produce high-quality seed.
- Survival and growth rate of Cambodia indigenous snakehead should be optimized through development of F2, F3 and F4 generation broodstocks and genetic selection of wild capture snakehead collected from different natural water bodies in Cambodia.
- Practical formulated diets should be developed for snakehead broodstock, fry and fingerlings to replace SSF from capture fisheries
- Extension services should be provided to farmers on techniques for snakehead breeding, weaning and grow-out using formulated diets
- Government, business and development partners should be encouraged to invest in the value chain of snakehead aquaculture development, especially the private sector to formulate and improve commercially manufactured feed that is better integrated into local economy with fewer imported ingredients and lower prices.

QUANTIFIED ANTICIPATED BENEFITS

This research provides information on domesticated breeding, weaning and growing out of snakehead fish, especially development of Cambodia's snakehead aquaculture technologies, in order to lift the ban on snakehead culture in Cambodia. The following are quantifiable anticipated benefits:

- Scientists, researchers, government fisheries officers/managers and policy makers, extension workers, NGO staffs, private sector and university lecturers and students working on the issues of snakehead aquaculture in Cambodia as well as in other Mekong riparian countries were better informed about research methods and findings, and have better recommended policies and strategies for sustainable snakehead aquaculture.

- Three undergraduate students were supported and trained by this investigation through their B.Sc. thesis research.
- Benefits to the US include improved knowledge and technologies on domestication of freshwater fish species for aquaculture and this aquaculture is considered as a climate change adaptation measure.

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TABLES AND FIGURES

Table 1: Cross breeding between wild and domesticated snakehead in Vietnam

Treatment	Gross breeding
1	Domesticated female (♀) x Domesticated male (♂)
2	Domesticated (♀) x Wild male (♂)
3	Wild female (♀) x Wild male (♂)
4	Wild female (♀) x Domesticated male (♂)

Table 2. Spawning parameters of different snakehead in Vietnam

Treatment	Spawning rate (%)	Fecundity (egg/kg)	Fertilization rate (%)	Hatching rate (%)
1 (DxD)	100	35,121	71.5±27.7	39.7±32.3
2 (DxW)	100	36,012	85.7±24.6	70.2±28.5
3 (WxW)	90	54,567	86.7±32.6	92.4±9.5
4 (WxD)	100	42,115	67.1±39.9	66.4±36.2

Note: D; domesticated; W: wild

Table 3. Abnormal rate, egg diameter and length of larvae of different snakehead in Vietnam

Treatment	Abnormal rate (%)	Egg diameter (mm)	Length of larvae (mm)	
			At hatching	After yolk absorption
1 (DxD)	6.5	2.75	6.08±0.38	11.37
2 (DxW)	8.5	2.78	5.81±0.43	11.40
3 (WxW)	1.2	2.80	6.01±0.40	11.67
4 (WxD)	2.2	2.72	5.87±0.43	11.69

Table 4. The growth of fingerling from different snakehead in Vietnam

Treatment	Initial length (cm)	Final length (cm)	Initial weight (g)	Final weight (g)
1 (DxD)	0.608	4.61±0.78	0.0021	1.15±0.54
2 (DxW)	0.581	4.66±1.17	0.0020	1.13±0.63
3 (WxW)	0.601	4.59±0.87	0.0019	1.04±0.50
4 (WxD)	0.589	5.12±1.18	0.0020	1.50±0.81

Table 5. Survival rate of different snakehead fingerling from different in Vietnam

Treatment	Survival rate (%)
1 (DxD)	45.6±16.9[a]
2 (DxW)	41.3±10.0[a]
3 (WxW)	41.0±15.5[a]
4 (WxD)	42.0±11.8[a]

Data are means of three observations ± SE. Means in the same column with the same superscript are not significantly different (P<0.05).

Table 6. Survival and growth of *Channa striata* of Vietnamese and Cambodian origin during weaning (hatchery phase) and grow-out phases of production. Both survival rate and cannibalism rate represent percentages of all the fish stocked in a given treatment. FCR is feed conversion rate. Values (mean ± SE) in a column followed by the same letter are not significantly different.

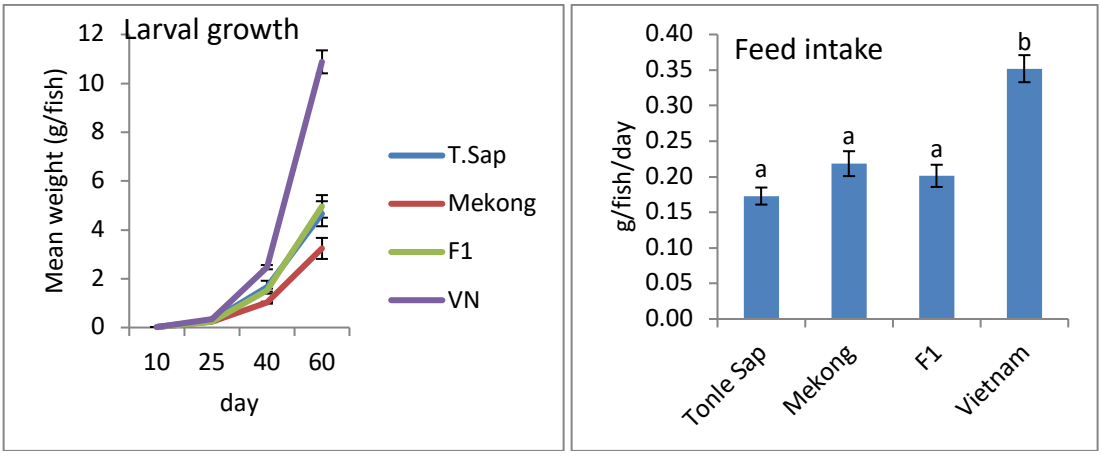
	Survival rate (%)	Cannibalism rate (%)	Weight gain (g.fish^{-1})	FCR	Yield.hapa^{-1} (kg)
Hatchery phase					
Vietnam	41.6 ± 3.4 B	41.1 ± 3.1 B	10.88 ± 0.47 A	1.63 ± 0.11 A	-
Tonle Sap	55.8 ± 2.9 A	42.0 ± 3.0 B	4.66 ± 0.50 B	1.91 ± 0.11 A	-
Mekong	39.0 ± 3.8 B	57.2 ± 4.0 A	3.24 ± 0.43 B	3.82 ± 0.86 B	-
F1	53.8 ± 3.6 A	40.2 ± 3.2 B	4.96 ± 0.46 B	2.06 ± 0.09 B	-
Grow-out phase					
Vietnam	80.8 ± 4.4 A	12.3 ± 4.0 A	324.2 ± 8.0 A	1.57 ± 0.06 A	81.0 ± 3.6 A
Tonle Sap	67.0 ± 5.6 A, B	27.4 ± 5.3 B	148.1 ± 16.4 B	1.90 ± 0.08 A	27.3 ± 1.93 B
Mekong	50.7 ± 9.4 B	45.1 ± 8.8 B	132.9 ± 19.0 B	2.08 ± 0.24 A	17.4 ± 2.91 B
F1	77.6 ± 5.0 A	21.0 ± 4.7 A	147.2 ± 17.7 B	1.59 ± 0.05 A	35.0 ± 3.44 B

Table 7. Economics of experimental snakehead cultured per hapa (3m x 1m x 1.5m)

Treatments	Total cost (feed) (thousand KHR/hapa)	Total income (thousand KHR/hapa)	Profit (thousand KHR/hapa)
Vietnam	512	648	136
Tonle Sap	209	218	9
Mekong	160	139	-21
F1	225	280	55

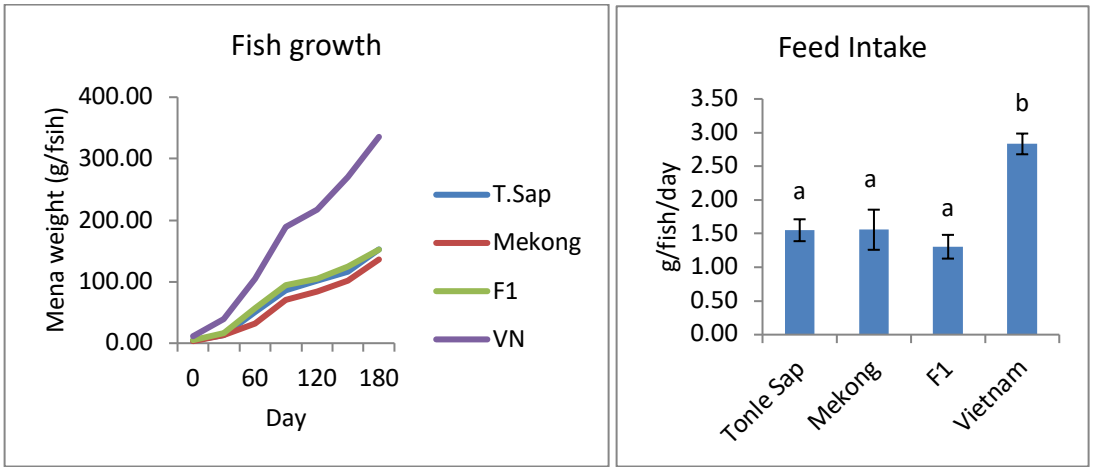
Table 8. Economics of experimental snakehead cultured per kg fish produced

Treatments	Total cost (feed) (thousand KHR/Kg fish)	Total income (thousand KHR/Kg fish)	Profit (thousand KHR/Kg fish)
Vietnam	6	8	2
Tonle Sap	7.7	8	0.3
Mekong	9.4	8	-1.4
F1	6.4	8	1.6



(a) (b)

Figure1. Weight gain (panel a) and feed intake (panel b) of larvae spawned from different broodstock fish as indicated and subjected to the same weaning and rearing protocol from 10 to 60 d after hatching.



(a) (b)

Figure2. Weight gain (panel a) and feed intake (panel b) of weaned fish from the hatchery phase (spawned from different broodstock fish as indicated) and subjected to the grow-out rearing protocol for 6 months beginning at 60 d after hatching.

Figure 3. Snakehead spawning, weaning and rearing activities in Vietnam

Figure 4. Wild snakehead collection and condition in Cambodia

Figure 5. Induced spawning of snakehead brooders in Cambodia

Figure 6. Snakehead egg collection and incubation after spawning in Cambodia

Figure 7. Weaning snakehead larvae in hapa nets and in tanks in Cambodia

Figure 8. Snakehead fingerling after 60 days of weaning in Cambodia

Figure 9. Grow-out snakehead in hapa nets for 6 months in Cambodia