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1 Challenges and opportunities in achieving sustainable mud crab 2 aquaculture in tropical coastal regions

3

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13 Highlights:

- 14 • Small-scale mud crab aquaculture can be sustainable in tropical coastal regions
- 15 • Economic, social and environmental sustainability of mud crab aquaculture expansion is
16 dependent on access to affordable loans, sustainable feeds, training and survival rate.
- 17 • Ensuring high survival rate of mud crabs, influenced by climate change, disease and
18 cannibalism, is critical for aquaculture success.

19 Keywords: fish farming, crustaceans, subsistence, livelihoods, benefit-cost analysis

20

21 Abstract

22 Aquaculture plays a significant role in food security and provides livelihoods and employment for
23 millions of people among coastal communities worldwide. However, the growing aquaculture
24 sector has also created debates around its long-term ecological sustainability, economic viability,
25 potential social inequalities and governance issues. We investigated the perceived challenges and
26 opportunities to achieving sustainable mud crab aquaculture in tropical coastal regions by using
27 the case study of coastal mud crab farms in Andhra Pradesh, India. Informed by perceptions and
28 indicative financial data from a sample of stakeholders we investigated the potential economic
29 outcomes under different scenarios representing varying yield levels, risk factors and project time

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30 periods. The main risks identified by the stakeholders were associated with the limited supply of
31 mud crab seeds and the lack of access to governmental and non-governmental support schemes.
32 There are no financial buffers, therefore major disease outbreaks or extreme weather conditions
33 caused by climate change would lead to a loss of livelihoods. This paper also highlights the most
34 critical factor determining the level of success of mud crab farming being the crab survival rate
35 which is influenced by a variety of factors including increasing sea surface temperature. The results
36 of this study show that small-scale mud crab farming has fewer risks and higher flexibility involved
37 than large-scale mud crab farming. It could be an economically sustainable enterprise and serve
38 as a tool for poverty alleviation in developing countries if microfinance support and training is
39 available.

40 1. Introduction

41 Global human population growth along with increasing fishing intensity and capacity are major
42 factors leading to the depletion of wild fish stocks, which consequently has resulted in the rapid
43 expansion of the aquaculture sector in the last three decades in coastal and ocean regions. In
44 2017 global production from aquaculture was 80 million tonnes, encompassing 425 fish and
45 shellfish species (Naylor *et al.*, 2021). Aquaculture is now the fastest growing food production
46 sector in the world and has a direct impact on food security and poverty alleviation of the rural poor
47 in coastal regions (FAO, 2022). Small-scale aquaculture has been identified as one of the
48 promising economic enterprises generating income and employment opportunities to local
49 communities (Toufique and Belton, 2014). However, some of the farming practices, in particular,
50 shrimp (Penaeidae) and milkfish (Chanidae) farming, are linked to the extensive destruction of
51 mangrove forests and coastal wetlands during 1980s and 1990s (Naylor *et al.*, 2000). The first
52 two decades of aquaculture sector development also saw significant problems with effluent
53 discharge, the introduction of non-native species and extensive use of wild seed (early life stage
54 and/or juveniles) to stock aquaculture ponds (e.g., Naylor, 2000; Primavera, 2006). This has been
55 linked to weak governance mechanisms and policies supporting foreign exchange without fully
56 assessing environmental impacts (Hishamunda *et al.*, 2009; Genschick, 2011). In addition to the

57 negative environmental impact, social issues such as the exclusion of small-scale fishing
58 communities were also seen (Béné, 2015; Blythe *et al.*, 2015). However, more recently significant
59 steps have been taken to achieve a sustainable aquaculture sector (Eigaard *et al.*, 2014; Naylor
60 *et al.*, 2021). Acknowledging the negative associations with the aquaculture sector is important for
61 ensuring that any emerging aquaculture farms have minimal adverse environmental and social
62 impacts. Aquaculture at the coast can pose significant governance issues as coastlines are often
63 the least governed spaces while being used by multiple users for various purposes (Mansfield,
64 2004; Foley and Mather, 2018). Furthermore, being at the interface between the land and sea,
65 governance of coastal aquaculture entails management of common pool resources (water bodies)
66 (e.g. Osmundsen *et al.*, 2020; Partelow, 2021), property rights (e.g. Tecklin, 2016), supply chains
67 (e.g. Bush *et al.*, 2019; Bottema *et al.*, 2021) and competition with fisheries and agriculture (e.g.
68 Tveterås and Tveterås, 2010).

69 One of the most valuable crustaceans in the Indo-Pacific region is the mud crab of the genus *Scylla*.
70 Mud crab fishing and farming in South Asia have been practised for decades and it serves as a
71 significant source of income for small-scale fisher communities in these regions as well as a vital
72 protein source (Keenan, 1999). *Scylla serrata* is the most economically important species among
73 the four *Scylla* species due to its large size and demand in the domestic and export market of many
74 countries (Flint *et al.*, 2021). It can be farmed in a relatively simple setup, including mangrove pens
75 and earthen ponds previously used for shrimp farming. It is known to be hardy and it tolerates wide
76 temperature and salinity gradients, yet its cannibalistic behaviour accounts for a relatively high
77 mortality rate (Alberts-Hubatsch *et al.*, 2016). Furthermore, although it is possible to rear crab
78 larvae in hatcheries, large-scale commercial hatchery production is still limited by low survival rates
79 (Quinitio *et al.*, 2001), depending on the optimisation of rearing conditions, nutrition and disease
80 management (Nghia *et al.*, 2007) and crab farms still often rely on wild caught juvenile crabs.

81 A widely accepted narrative is that fish is vital for food security for rural poor communities. Small-
82 scale aquaculture can be a subsistence activity or a form of livelihood diversification contributing
83 to poverty alleviation (Little *et al.*, 2010). However, the counterargument is that the fish farmed by

84 these communities are consumed by the middle class instead and often exported to the Global
85 North (Beveridge *et al.*, 2013; Golden, 2016), therefore not solving local food security and/or
86 poverty challenges. Amid these two narratives, an alternative narrative of aquaculture as a small-
87 and medium-scale enterprise (SME) has emerged highlighting the indirect effects of aquaculture
88 on poverty alleviation. Developing aquaculture as SME can create growth linkages – employment
89 opportunities, demand for feed and other inputs (Filipski and Belton, 2018).

90 Owing to the high economic value of *S. serrata* and the prospect of environmentally sustainable
91 farming set-ups, this study aims to: 1) determine the perceived opportunities and limitations to
92 mud crab farming in tropical coastal regions and 2) assess the potential of mud crab aquaculture
93 as a sustainable small- and medium-size enterprise.

94 2. Materials and methods

95 2.1. Study area and data collection

96 The study was conducted in Andhra Pradesh, a tropical coastal region in southeast India and the
97 leading state of aquaculture production, contributing 40% of the total farmed fish export value for
98 India (Subramanyam and Prasad, 2017). The main aquaculture species in this region are prawns,
99 catfish and carp, and increasingly mud crabs. Socioeconomic data on small-scale mud crab
100 farming were collected by using a structured questionnaire through direct face-to-face interviews
101 in October 2019. The interviews were conducted in the local language Telugu with the aid of a
102 translator. The questionnaire was divided into five sections – 1) stakeholder perceptions of farm
103 management practices of mud crabs, 2) access to market and extension services (such as
104 agencies providing information and training), 3) costs and returns of production, 4) environmental
105 issues and 5) demographics. A snowball sampling approach (research participants help identify
106 other potential participants) was used after the first respondents were identified by local
107 authorities and researchers. The snowball sampling approach was chosen as no extensive
108 registers are available for crab farms in Andhra Pradesh. Being a type of purposive sampling, this
109 approach allows for building up a sample based on the research project's aims (Robson, 2015). In

110 total 37 respondents were interviewed in nine locations across a 500 km transect, providing
111 sufficient indicative perception and financial data to inform the scenario analysis (Fig.1).

112 2.2. Data analysis

113 The data were divided into two groups according to the size of the farm – small-scale (less than 2
114 ha) and large-scale (more than 2.01 ha). The size categorisation was based on the small-scale
115 farm definition by the High Level Panel of Experts on Food Security and Nutrition of the Committee
116 on World Food Security (HLPE, 2013). There are no clear cut-offs for small-, medium- and large-
117 scale agriculture and aquaculture farms. For example, with regards to agriculture, 73% of small
118 holders worldwide have access to less than 1 hectare of land (HLPE, 2013), meanwhile, a 10 acre
119 (4 ha) cut off to define small-scale aquaculture in Myanmar was used by Filipiski and Belton (2018).

120 2.2.1. Stakeholder perception analysis

121 The questionnaire was based on the themes identified through a literature search on the drivers
122 and limitations of [the](#) aquaculture sector. These largely coincide with challenges and opportunities
123 reported by Naylor *et al.* (2000; 2001). The themes are land and water resources, seed (initial
124 stock), feed, disease, financial and legislative support, market demand and conditions and climate
125 change. Although our output was quantitative, the results were analysed acknowledging the theme
126 they cover. The statistical analysis was conducted using the Statistical Package for Social
127 Scientists (IBM SPSS Statistics 24). The Chi-Square test of independence was used to determine
128 whether there was a significant relationship between the variables.

129 2.2.2. Financial analysis – a snapshot

130 As long-term financial data are difficult to obtain, a snapshot analysis of one harvest (year), was
131 conducted to obtain indicative financial information to inform a scenario analysis. Cost and
132 revenue data gathered were used to calculate the profitability of mud crab aquaculture for one
133 year (2019). The following indicators were calculated from the survey data: total costs (TC), total
134 revenue (TR), net profit (NP), benefit-cost ratio (BCR) and return on an investment expressed as a
135 percentage (ROI%). Total revenue was calculated from the amount of the harvested production

136 and the selling price at the time. Six respondents were yet to harvest their mud crabs at the time
137 of the survey, and thus were unable to provide information on revenue, and were therefore
138 excluded from further analysis on profit.

139 2.2.3. Scenario analysis of potential economic outcomes

140 Crab aquaculture is very dynamic and harvest successes depend on various factors, including
141 cannibalism, climate change and disease. Therefore, to determine the potential economic
142 outcomes for aquaculture in SE India various scenarios were developed to represent a range of
143 financial, biological and ecological conditions. The financial data from stakeholder surveys were
144 used to guide the values of costs and prices applied in these scenarios. The five scenarios (high,
145 medium, low, high/low and medium/low) represented three harvest rates based on the literature
146 and our empirical findings. The maximum harvest is set to be 45% (high scenario) (Moksnes *et al.*,
147 2015b; Islam *et al.*, 2018; Mwaluma and Kaunda-Arara, 2021) and the mean harvest is set to be
148 23% (medium scenario) based on the mean survival rate seen in this study and also on findings
149 by Mirera and Moksnes (2014). The survival rate for the low scenario is 10% (Mirera and Moksnes,
150 2014). The high/low and medium/low scenarios were included to show the high variability of
151 harvest successes.

152 The Net present value (NPV) of costs and benefits was calculated over 5, 10, and 15 years with
153 different harvest successes (Table 1). Such timeframes were chosen as fishers and aquaculture
154 practitioners respond to changes and might switch to species with higher market prices or species
155 that are easier to maintain. To account for variable market conditions, NPV was estimated by using
156 three discount rates – low 5%, medium 10% and a higher discount rate of 15% (Bag *et al.*, 2014;
157 Anokyewaa and Asiedu, 2019; Namonje-Kapembwa and Samboko, 2020). Mean total fixed and
158 variable costs and profit were calculated based on the values given by the respondents. Total
159 revenue was calculated using the mean number of crablets stocked per culture. . Crablets were
160 restocked every year as they were fully harvested at the end of the season.

161 For all the scenarios initially it was assumed that: i) Crabs were 1st quality class size (big) ; ii) The
162 selling price was the mean price reported by respondents in October 2019 for the 1st quality class

163 size (big); iii) The initial stock was the mean number of crabs stocked for small-scale and large-
164 scale farms; iv) Mud crab farmers have one crop per year and the growth period is between 5 and
165 6 months.

166 A sensitivity analysis was carried out to account for changes in input variables such as the selling
167 price and size of the crab. Two selling prices were tested - the highest reported selling price and
168 the lowest reported selling price). Two crab sizes were applied –a high weight of 700 g each and a
169 low weight of 300 g each. Each change in input variable was tested independently and applied for
170 all the scenarios with a 10% discount rate for 10 years.

171 3. Results

172 3.1. Demographics and characteristics of mud crab farms

173 All respondents were male, aged from 26 to 81 years with an average age of 43 years and with
174 Telugu as their native language. Over half (57.6%) of the crab farmers interviewed have been
175 undertaking mud crab aquaculture for less than five years. From those who have been involved in
176 crab farming for six or more years, five respondents have been farming crabs for 15 years. The
177 aquaculture ponds varied in size from 0.405 ha to 16 ha, yet the majority of respondents (64.9%,
178 n=24) had small-scale mud crab farms, ranging in the size from 0.405 ha (1 acre) to 2 ha (Table
179 S1). The two largest large-scale farms covered 16 and 12 ha farms, while the majority of the large-
180 scale farms were between 2.01 and 4.9 ha in size. The majority of large-scale farmers (53.8%)
181 owned the land, the farms were located on or leased additional land, while small-scale farmers
182 tend to lease the land or used common resources. All respondents from Krishnapatnam (KRI) were
183 undertaking crab farming in a natural water body – a large lake-like water basin that has been
184 created after building a thermal power station in the area. The majority of respondents had one or
185 three one-acre ponds, yet one respondent had five ponds (5 acres or 2.03 ha), which placed him
186 into the large-scale farming group. Furthermore, five respondents, formerly fishers, from Tallarevu
187 (TA) and Mummidivaram (MU) had acquired 1 ha in the mid-1980s from the District Rural
188 Development Agency (DRDA) after being trained in aquaculture. One respondent had a cage
189 culture, where crabs were kept in individual boxes partially submerged in the water. All of the

190 respondents were mainly involved in 'grow out' aquaculture which means acquiring and farming
191 early juvenile stage crabs to reach their adult stage in the aquaculture system. The juvenile stage
192 crabs could be purchased from a commercial mud crab hatchery, but at the time of the study, there
193 was only one such hatchery providing for crab farmers across the whole of India. The majority of
194 respondents stocked around 800 to 1,200 instars (small early-stage juvenile crabs 0.5 cm in
195 carapace width) and 400 to 500 crablets (slightly larger juvenile crabs from 2 cm carapace width)
196 per acre. Small-scale farmers on average stocked 2,043 crablets at the beginning of the season,
197 while the mean number for large-scale farmers was 5,846 crablets. Instars and crablets are terms
198 used in the aquaculture sector in India to refer to different sizes of not yet sexually mature juvenile
199 crabs (Rajiv Gandhi Centre for Aquaculture, 2013). Therefore, due to the high competition to obtain
200 seeds, the majority of respondents also relied on wild stock collected by local fishers or procured
201 from crab dealers in Chennai. The majority described access to crab seed to be very difficult
202 (51.4%) or somewhat difficult (27%) (Fig.2). The crabs were kept in the ponds for 3 to 8 months,
203 with 5.3 months being the average duration. The survival rate varied significantly from as low as
204 2% to as high as 60%, with a mean survival rate of 23% (including mass mortalities).

205 Respondents did not face any issues with water availability as the farms were located near rivers,
206 man-made canals or seaside (Fig.2). The majority of large-scale farmers (69.2%) regularly checked
207 water salinity, temperature, pH and bacterial load or treated water chemically. The chemicals
208 applied, such as fertiliser dolomite lime to balance pH, fertiliser diammonium phosphate (DAP),
209 urea and superphosphate, are commonly used in more intensive aquaculture setups such as
210 shrimp aquaculture (Gräslund and Bengtsson, 2001). The Chi-Square test of independence
211 indicated that there is a statistically significant difference between the type of water quality
212 maintenance and the main source of income ($p = 0.019$). Chemicals are used mainly by those
213 involved both in shrimp and crab farming.

214 Access to feed was assessed as easy by 54.1% of large-scale farmers, yet 47.4% and 5.3% of
215 small-scale farmers identified access to feed as somewhat difficult and very difficult, respectively.
216 Thus, a correlation between the perception of access to feed and the scale of crab farms was found

217 (p = 0.042). Small-scale crab farmers mainly used chopped fresh fish as feed, while the majority
218 of large-scale farmers used dried fish. The amount of feed given greatly varied between farms, but
219 on average small-scale farmers used 1608 kg of live fish per culture, which takes around 5 to 6
220 months) and large-scale farmers used 7600 kg/culture. Feed was mainly procured from local
221 fishers or landing sites. For 43.2% of respondents, mud crab farming was their primary source of
222 income, followed by crab and shrimp farming (alternating between crabs and shrimps). Small-scale
223 mud crab farmers had ~~a more diversified source~~more diverse sources of income compared to
224 large-scale farmers. For instance, a primary and secondary source of income for small-scale
225 farmers was crab farming (42% and 12%, respectively), crab and shrimp farming (33% and 4%),
226 small business (13% and 4%), shrimp farming (8% and 4%), and wage labour (4% and 17%). One
227 small-scale farmer was also involved in fishing as a secondary activity. Meanwhile, large-scale
228 farmers were involved in crab farming (43%), crab and shrimp farming (43%) and only shrimp
229 farming (7%) as primary income generating activity, and wage labour was only a secondary activity
230 for one farmer and a tertiary activity for another farmer. No large-scale farmer was involved in small
231 business ventures or fishing.

232 3.2. Perceptions of the market, access to support and environmental issues

233 Respondents were asked about access to the market, information and assistance. As expected
234 for this species, the majority (83.8%) sold the live crabs to a middleman who in turn sold them to
235 an exporter for shipment overseas (e.g. to Singapore). The remaining 16.2% sold their crabs in the
236 local market. Very few respondents (5.4%) were not satisfied at all with the service of their
237 middleman, while the majority (70.3%) were somewhat satisfied. The main reason for not being
238 'very satisfied' was the uncertainty of whether the prices set by the middlemen are fair. The price
239 depends on the size and the quality of the crab, and it fluctuates depending on the international
240 demand and season. The average price per kilogram reported by crab farmers in October 2019 for
241 the 1st class (XL) crab (>800g, intact) was £15.48/kg, £10.13/kg for big, 500-800g crab, £5.79/kg
242 for 300-500g intact crab and £3.12/kg for 300-800g crab with physical damage. The most
243 common way to deliver harvested crabs was by transport organised by a middleman. All of the

244 large-scale farmers used this option, while small-scale farmers also used their own transport
245 (4.2%) or used public transport (12.5%).

246 Access to training in aquaculture practices was assessed as very difficult by the majority of the
247 respondents along with almost impossible access to loans and subsidies (Fig .2). More than half
248 of mud crab farmers (75.7%) thus disagreed with the statement that they receive enough support
249 from various organisations, yet 97.3% said that they would be willing to expand if they received
250 support. Asked whether they perceive mud crab farming as a profitable activity, 70% responded
251 positively. Yet at the same time, 70% said that mud crab farming is not a stable source of income.
252 Although mud crab farming is not perceived as an unambiguously stable or profitable activity, all
253 of the respondents unanimously agreed that they would encourage their friends and family to
254 undertake mud crab farming.

255 The majority (48.6%) perceived that the wild mud crab population has slightly decreased since they
256 have been involved (varying between 2 and 23 years) in mud crab farming, and 29.7% reported it
257 to be significantly decreasing. The biggest environmental issues were reported to be increased
258 water temperature and water pollution and saltwater intrusion. Consequently, these were
259 mentioned as the reasons for disease and mortality of crabs as 78.4% of respondents had noticed
260 sick or temperature-affected crabs in their ponds, thus highlighting the direct and indirect effects
261 of climate change on mud crab aquaculture. Mangrove destruction harming their crab culture was
262 only reported by small-scale crab farmers.

263 3.3. Assessing profitability of mud crab farming

264

265 Small-scale farmers invested the most in fencing, feed and crablets procured in kilograms, while
266 large-scale farmers spent the most on crab instars and crablets sold per piece and digging and
267 preparing ponds (Table 2). Besides, one of the biggest differences was the number of people
268 involved in harvesting and thus its impact on costs, which was on average ~£139 (13,452 Indian
269 rupees) per culture for a small-scale farm and ~£272 (26,192 Indian rupees) per culture for a
270 large-scale farmer. Two large-scale farmers did not report any fixed costs. One of them owned the
271 land, thus there were no land lease expenses and other fixed costs might have been accounted

272 for in the variable costs reported. The other farmer only reported costs on crab seed and labour,
273 although was leasing 3 acres of land beside the 7 acres he owned. The total cost of production
274 was more than two times higher for large-scale farmers compared to small-scale farmers. Bigger
275 investment, however, also can mean bigger losses in case of disease outbreaks. Four small-scale
276 farmers and two large-scale farmers lost all of their crabs due to increased water temperature or
277 white spot virus (WSV) outbreaks, resulting in a significant financial loss in the production year
278 2019. Yet even the farmers who did not lose all of their harvests faced a significant decrease in
279 numbers compared to their previous harvests due to identical factors. The financial indicators
280 varied significantly between mud crab farmers, yet the average net profit was only positive for the
281 small-scale farms. However, it should be noted that it was largely because of the farms with ROI of
282 622% and 998%. These farmers owned their land, had minimal labour and transportation costs
283 and the highest costs were associated with feed, but did not report any maintenance costs. They
284 also reported high total harvest success, yet without detailed information on the crab weight they
285 sold. This shows how mean values of indicators and ratios are not always indicative of the
286 individual feasibility. While the mean value is positive (1.4), more than half (n=13) of the small-
287 scale farmers included in this analysis had a low BCR indicator (value above 1 indicates profit) and
288 a negative ROI% (Table 3). Only two large-scale farms had positive ROI% and beneficial BCR.
289 Overall, it can be concluded that this year's harvest brought financial losses to the majority of the
290 mud crab farmers regardless of the scale of the farm. Other authors have reported the mean BCR
291 of *Scylla* sp. [aquaculture](#) to range from as low as 0.39 (Moksnes *et al.*, 2015a) to as high as 1.97
292 (Petersen *et al.*, 2013) (Table 4).

293 3.4. Future feasibility assessment of mud crab farming

294 Analysis of costs and benefits of one isolated year gives a static picture of a business that is
295 influenced by many various factors affecting the success of the harvest. To investigate the longer-
296 term feasibility of the mud crab enterprise the net present value of costs and benefits was
297 calculated based on the mean costs and benefits in five different harvest scenarios, with three
298 different discount rates and over three different time periods. The mean total fixed costs,

299 calculated from the survey data, were £601 (57,863 Indian Rupees) for small-scale farmers and
300 £2139 (205,923 Indian Rupees) for large-scale farmers. Mean total variable costs were
301 significantly higher – £1709 (164,530 Indian Rupees) and £5828 (560,938 Indian Rupees) for
302 small and large-scale farmers, respectively. Scenario analysis outcomes show that if the crab
303 survival rate each year is 23% (medium scenario, mean survival rate recorded by the respondents),
304 both small- and large-scale mud crab farmers gain moderate profit in long term (Fig.3, Table S2).
305 The two most profitable scenarios are the high and the high/low scenario, the latter indicating that
306 for long term profit, the effects of mass mortalities can be reduced by obtaining higher survival
307 rates in the following year. The low scenario unsurprisingly showed that all farmers would suffer
308 significant losses, yet while the medium/low scenario would bring losses to large-scale mud crab
309 farmers, small-scale farmers would still obtain a positive net present value (NPV), albeit low.

310 The sensitivity analysis showed that the NPV in the case of the high scenario would increase by
311 38% for small-scale farmers and by 43% for large-scale farmers if the price was to increase to
312 £12.46/kg. If the crab size was 700g, the NPV in the case of the high scenario would increase by
313 65% for small-scale farmers and by 75% for large-scale farmers. (Fig.4, Table S3, Table S4). At the
314 same time if the price decreased to £6.23/kg and the size of each harvested crab was 300g, both
315 small- and large-scale mud crab farms would experience a decrease in profit in the high scenario
316 case and experience loss of income in the high/low variable scenario. The highest losses and gains
317 are seen in the medium/low scenario and in the case of the low scenario, indicating that the
318 survival rate is a dominant factor.

319 4. Discussion

320 4.1. Perceived resource opportunities and limitations

321 A number of resources are required for crab aquaculture and while the availability of water
322 resources in coastal India is a significant advantage compared to other countries such as Tanzania
323 (e.g., Mulokozi *et al.*, 2020) and Cambodia (e.g. Richardson and Suvedi, 2018), access to land for
324 establishing earthen ponds can be limited. Andhra Pradesh is well known for its intensive inland
325 aquaculture sector for which earthen ponds and canal systems have been built (Belton *et al.*,

2017), thus it is common to undertake intensive crab culture with higher stocking densities. Yet, such farming can exclude certain communities that would benefit from livelihood diversification such as artisanal fishers who often do not possess more than their homestead land and suffer from social inequality (Bakshi, 2008). Land costs can contribute as high as 70% of total expenses (Sathiadhas and Najmudeen, 2004). Land in an agrarian society such as India, where agriculture provides a livelihood for 58% of India's population (IBEF, 2020), is a valuable commodity. The average size of the land owned by a rural household in Andhra Pradesh is 0.471 ha and 47% of all operational holdings in the state can be described as marginal, owning 0.002 to 1.00 ha of land (NSSO, 2016). The majority of the respondents of this study, however, had access to more than 0.6 ha of land for crab farming and did not consider access to land to be a barrier. A significant proportion of these crab farmers were also involved in shrimp farming, thus potentially having had access to training or other support. Thus, it highlighted that mud crab farming in Andhra Pradesh was perceived as a large-scale business opportunity rather than as a small-scale sustainable diversification enterprise. While the land is not a ubiquitous limitation for the crab farmers recruited in this study, the lack of access can act as a barrier for those needing livelihood diversification due to low income (Belton *et al.*, 2014, Little *et al.*, 2010). This was shown to be the case in an earlier study, investigating the limitations of undertaking crab farming among fisher communities in southwest India (Apine *et al.*, 2019). Furthermore, differences in land lease costs per hectare indicate that communities could be affected by economies of scale. Unit costs decrease with the increase of scale, thus unit costs for smallholders are higher compared to large-scale farm owners (OECD, 1993). Thus, incoherent property rights systems have the potential to limit community members interested in small-scale mud crab farming. Meanwhile, limited access to private land could stimulate undertaking sustainable farming practices in existing water bodies, such as mangroves and common water bodies. This could potentially create other issues such as environmental degradation if not managed properly and sustainably (Taskov *et al.*, 2021). Coastal areas of Andhra Pradesh have undergone significant land use changes since 1977 and a high proportion of agricultural land as well as 3.8% of mangroves [have](#) been converted to aquaculture farms (Bagaria *et al.*, 2021; Jayanthi *et al.*, 2022). Simultaneously it is experiencing a high rate of

354 aquaculture farm abandonment (Jayanthi et al., 2019). Transforming earthen ponds ~~to~~ back to
355 agricultural land or mangroves could be difficult (e.g. de Lacerda et al., 2021), thus repurposing
356 them for other type of aquaculture, such as mud crab farming, could be an efficient way of
357 managing these coastal resources. However, the above-mentioned statistics also indicate that
358 reusing old shrimp farms should be a priority over creating new aquaculture farms.

359 Another fundamental resource required for aquaculture is seed. A technological breakthrough in
360 the early 2000s (Quinitio et al., 2001) made it possible to obtain hatchery-reared mud crab
361 juveniles. However, capacity and facilities differ greatly in the Indo-Pacific region. In India, to date,
362 there is only one working commercial mud crab hatchery providing for all the farmers in the country,
363 although plans of establishing a second mud crab hatchery have been made since the year 2017
364 (Sengupta, 2017). At the same time the East African region still relies heavily on wild seeds
365 (Moksnes et al., 2015a). Limited seed supply can be a potential source of further inequality as
366 large-scale farmers are more likely to be able to purchase seeds from hatcheries that are not
367 nearby and cover travel costs. Furthermore, small-scale fishers and fish farmers often tend to be
368 marginalised and not accounted for (Song et al., 2018). Results of this study confirmed that limited
369 access to seeds currently is a barrier for the majority of mud crab farmers and the unpredictability
370 has a significant economic impact.

371 One of the most controversial aspects of the whole aquaculture sector, including mud crab farming,
372 is the use of so-called “trash fish/low-value fish” as feed. Trash fish and bycatch are also used to
373 produce fishmeal, a commercial product widely used in aquaculture/mariculture, land animal
374 farming and pharmaceuticals (Shepherd and Jackson, 2013). As the aquaculture sector expands,
375 the demand for fishmeal increases creating a ‘fishmeal trap’ – aquaculture is seen as an
376 alternative to wild fish resources but at the same time is dependent on these resources (Wijkstrom
377 and New, 1989; Ankomah-Yeboah et al., 2018). This study showed that mud crab farms heavily
378 rely on “trash fish” – either as bycatch or as a targeted catch and based on observation most of
379 these fish were sardines and tilapia - widely consumed nutritious fish. As it requires potentially
380 thousands of kilograms of fish to feed one mud crab culture with greater than 70% mortality rate

381 for some farmers, it is important to question how sustainable the current practice of mud crab
382 farming is and how it can be improved. Basu and Roy (2018) found that high cost of crab feed was
383 one of the major constraints to mud crab farming in Bangladesh. Poor communities are not able
384 to afford farmed fish and crabs for their own nutrition and widely rely on more affordable wild-
385 caught fish, often those deemed “low value” (Joffre *et al.*, 2021). Yet, tilapia is considered to be
386 an invasive species in India that has escaped from the aquaculture farms into the wild (Singh,
387 2021), thus it could be argued that using tilapia as feed could help maintain the balance in wild
388 fisheries. However, before this could happen, further and more complex research is necessary
389 firstly, to assess the commercial value of the fish used as feed, secondly, to investigate people’s
390 preferences and thirdly, to conduct the stock assessment and future stock modelling.

391 4.2. Financial opportunities and limitations

392 The reason behind the potential for economic success of the mud crab is clear – high market
393 demand in both local and international markets. Foreign demand was also acknowledged to be
394 the main driver for shifting from shrimp cultivation to mud crab farming in Bangladesh (Basu and
395 Roy, 2018). A study based on FAO FishStat J Database showed that 85% of aquaculture production
396 from the ten biggest aquaculture producer countries is consumed domestically and in India, this
397 share is as high as 95% (Belton *et al.*, 2018). However, it is difficult to trace where the production
398 chain of the mud crab ends as there are no species-specific databases. Data sets on crabs might
399 include marine crabs and data sets on crustaceans usually include shrimps and prawns that would
400 account for the biggest share. The data from the International Trade Centre showed India is a net
401 exporter of all types of crabs and crab products, with an annual growth of 18% and the main
402 markets are China, Singapore, the United States of America, Taipei and Thailand (ITC, 2019). Yet,
403 there are no clear data on the total amount of produce and what share stays in the domestic
404 market. There is enough anecdotal evidence to support the importance of the domestic market in
405 the trade of mud crabs, yet the lack of official data sets can render identifying any signs of market
406 failure that can have a significant adverse impact on mud crab farmers.

407 Mud crab farming is perceived as a profitable, yet unsteady income-generating activity [due to the](#)
408 [unpredictable survival rates and the quality of crabs](#). However, the prospect of profit outweighed
409 the unpredictability and even a complete loss of stock did not discourage farmers to continue.
410 Thus, similarly to shrimp aquaculture, crab farming is 'like gambling' as several factors can
411 influence the outcome, shrimp farmers were found to be fully aware of risks and chose species,
412 intensity and risk management plans accordingly (Joffre *et al.*, 2018). Therefore, for mud crab
413 farmers, flexibility regarding the type of culture (grow-out or fattening), stocking density and the
414 length of culture and diverse source of income (especially for small-scale farmers) is their response
415 to mitigate and/or adapt to risks.

416 The results of various scenarios suggest that mud crab farming can be a feasible income-
417 generating activity, however the level of success is highly dependent on various factors such as
418 the discount rate applied, market price that mud crab farmers cannot affect, and the survival rate
419 of crabs that can partially be managed by monitoring and maintaining ponds. The most critical
420 factor in determining success (positive NPV), unsurprisingly, was found to be the survival rate of
421 mud crabs.

422 The survival rate and physiological or morphological state of crabs can be affected by water quality
423 (e.g. Botton and Itow, 2009), climate change effects such as heatwaves or droughts (e.g. Hamasaki,
424 2003; Ruscoe *et al.*, 2004) and disease (e.g. Waiho *et al.*, 2018; Sujan *et al.*, 2021). Furthermore,
425 cannibalism is a major issue and the main reason for low survival rates (Alberts-Hubatsch *et al.*,
426 2016). Several factors can determine survival rates and growth performance such as stocking
427 density (Mann *et al.*, 2007), the use of shelter (Mirera and Moksnes, 2014) and the type of culture
428 system (Islam *et al.*, 2018; Mwaluma and Kaunda-Arara, 2021). For instance, cage culture is
429 labour intensive as each animal is kept in an individual box, thus potentially having high labour
430 costs. Monoculture using seeds has been reported to obtain the highest return on investment,
431 followed by fattening (Marichamy and Rajapackiam, 2001). This, therefore, indicates how complex
432 and unpredictable mud crab farming is and that a collaboration between fishers, crab farmers,
433 researchers and the aquaculture industry is required to address these various challenges. Despite

434 the assumptions and based on research studies that indicate white spot virus outbreaks might be
435 rare, a major outbreak took place in *S. serrata* farms in Nagalayanka, Andhra Pradesh (CIBA,
436 2019), thus indicating that precautions must be taken to prevent the risks to infect crabs at their
437 juvenile stage.

438 Other studies in Asia have shown that mud crab fishing and farming is a lucrative business (e.g.
439 Ferdoushi and Guo, 2010; Jahan and Islam, 2016; Basu and Roy, 2018) if the highest possible
440 survival rates are achieved. Meanwhile in East Africa, where selling prices are lower compared to
441 Asia and the seed is limited as no commercial hatcheries have been established, profit is marginal
442 and cage culture, in particular, can result in a significant loss (Moksnes *et al.*, 2015a). Further
443 research on mud crab aquaculture report a wide range of BCR and net revenue depending on the
444 species, type of culture and country (Table 4). Most studies had higher mean BCR than in our study,
445 however only one study showed individual results. Basu and Roy (2018) reported a similarly wide
446 range of net revenue among crab farmers in Bangladesh. Based on the individual values on total
447 costs and total revenue reported by Basu and Roy (2018), it is possible ~~to calculate~~ that ROI% for
448 their study varied significantly between 13% and 354%, while there were no negative values. This
449 indicates that mean values can easily disguise any losses (or minimal success) individual farms
450 have experienced.

451 As in the case for most studies only mean ROI% values are available. Sathiadhas and Najmudeen
452 (2004) showed that return on investment varies depending on the type of culture, from 90% of
453 composite mud crab/fish or shrimp culture to 185% of grow-out system and 244% of crab
454 fattening. The ROIs% for *S. paramamosain* culture in Vietnam were 90% and 261% (Petersen *et al.*,
455 2013). Return on investment from other coastal aquaculture types in India ranged between 71%
456 ~~and to~~ 146% for open and semi-enclosed mussel farms in Goa, respectively (Lekshmi *et al.*, 2019),
457 to 241%/m³ for cage fish farming in Kerala (Aswathy and Joseph, 2019). This highlights two highest
458 ROIs% in our study as potentially exceptional. These two mud crab farmers were from the same
459 location and had 15-year experience with aquaculture, they owned the land the farms were located
460 on and one of them was applying chemicals that are commonly used in shrimp aquaculture (EDTA,

461 urea, single superphosphate and lime). Thus, the success could be explained by advanced
462 aquaculture practices and limited costs on maintenance and labour, yet to elucidate the main
463 reason would require further investigation. Furthermore, to fully assess the sustainability and
464 feasibility of mud crab farming, a longitudinal study is required, recording environmental
465 parameters and external factors affecting the market price.

466 Aquaculture at any scale involves various risks and having no access to subsidies and loans that
467 could provide a safety cushion makes it even more difficult (Kleih *et al.*, 2013). Thus, it hinders
468 community members who could potentially be interested in undertaking mud crab farming and
469 also existing crab farmers to continue or expand crab aquaculture. Poor access to loans was found
470 to be the second main constraint to mud crab farming in Bangladesh (Basu and Roy. 2018).
471 Fisheries and small-scale aquaculture always have been a sector with poor access to institutional
472 financial help such as credit. It was assessed in 2008 that 51.4% of farmer households did not
473 have access to institutional and non-institutional credit in India (Rangarajan, 2008). No clear
474 official statistics can be found regarding the situation currently, but it is likely that access to
475 institutional credits for agriculture, fisheries and aquaculture is still relatively poor. Thus,
476 microfinance is an essential tool for many in rural areas. In India, microfinance services could be
477 obtained from microfinance institutions that are regulated by the Reserve Bank of India and
478 recently non-banking microfinance institutions have been recognised (Rangarajan, 2008;
479 Ashaletha, 2018). Another important player in providing financial support for rural communities is
480 the National Bank for Agriculture and Rural Development (NABARD) and especially linking bank
481 services with self-help groups (SHGs).

482 This study was conducted before the COVID-19 pandemic, yet the pandemic has had a significant
483 adverse effect on capture fisheries and aquaculture, leaving communities with no income and
484 negatively affecting market prices (Manlosa *et al.*, 2021; Kiruba-Sankar *et al.*, 2022). In May 2020
485 it was announced that as part of the relief package to mitigate COVID-19 impacts, India's
486 government will assign USD 2.6 billion to support the integrated, sustainable, inclusive
487 development of marine and inland fisheries (Dao, 2020). More than half of these funds were

488 dedicated to marine and inland fisheries, and aquaculture, and the rest of it will be used to improve
489 infrastructure, including fishing harbours and market development. However, priority was given to
490 marine fisheries and mariculture, thus again potentially excluding mud crab farmers, especially
491 since, on a small-scale, mud crab farming, although relatively common and lucrative, is not
492 perceived as being as important as shrimp or fish farming by the state. Although the contribution
493 of small-scale aquaculture (FAO, 2009) and small-scale fisheries (Teh and Pauly, 2018) has been
494 widely recognised, often it lacks evidence in the form of institutional support. Davis and Ruddle
495 (2012) even argue that in the context of neoliberalism, support through co-management practices
496 or other seemingly small-scale holder empowering approaches is not possible, as social and
497 cultural values often in the core of smallholders, are not esteemed by neoliberalism. Thus,
498 indicates that any financial and legislative governmental support will likely benefit large-scale
499 practitioners and therefore the non-institutional sector (e.g. NGOs, SHGs) is left to play an essential
500 role in supporting smallholders.

501

502 5. Conclusion

503 Aquaculture is the fastest growing food production sector worldwide (FAO, 2022), while some warn
504 about over-optimism and potential decline due to environmental, technological and economical
505 reasons as well as socio-economic implications to marginal communities (Sumaila et al. 2022).
506 Therefore, understanding and assessing all pillars supporting the sustainability of aquaculture is
507 increasingly important. Small-scale fish and crustacean farming, in particular, requires attention
508 as [it](#) has [thea](#) potential to generate greater economic spillovers and provide better employment
509 opportunities than large scale fish farms or agriculture (Allison, 2011; Phillips et al., 2016; Filipski
510 and Belton, 2018; FAO, 2022). However, there are still challenges, such as, lack of technological
511 knowledge, lack of capital and limited involvement of women in decision making that hinder small-
512 scale aquaculture success in tropical coastal regions (e.g. Mulokozi et al., 2020; Aung et al., 2021;
513 Ragasa et al., 2022; Gwazani et al., 2022). Simultaneously small-scale fisheries and aquaculture
514 are especially vulnerable to climate, environmental and economic shocks (Short et al. 2021). Mud

515 crab aquaculture is an expanding sector and by using a case study approach, we investigated what
516 challenges and opportunities crab farmers in southeast India face and how they correspond to a
517 wider context.

518 The main challenges to achieving sustainable mud crab farming were found to be limited supply
519 of mud crab seeds, high mortality rates and the lack of support from governmental or non-
520 governmental organisations. There are no financial buffers, therefore in the case of a disease
521 outbreak or extreme weather conditions, farmers will suffer a huge loss. Meanwhile, perceived as
522 a delicacy with high nutritional value, mud crab has high demand in domestic and international
523 markets, ensuring competitive prices compared to other aquaculture species.

524 Through various scenarios based on the empirical indicative financial data, we found that the
525 development of small to medium-sized mud crab aquaculture in southeast India could be feasible
526 under certain conditions. Innovative solutions are required to reduce mortality to ensure that this
527 activity is profitable long term and reduce the uncertainty that farmers face. Especially as limited
528 financial support or advanced training is available. Currently mud crab farming heavily relies on so-
529 called trash fish, which often are juveniles, negatively affecting fish populations and potentially
530 making nutritious, low-value fish less accessible for marginalised communities. This study
531 indicates that there could be negative implications due to the high amounts of fish needed to feed
532 one mud crab culture, yet further systems-based studies are needed to fully understand the impact
533 on fish population structure and communities.

534 By comparing our findings with other studies and considering our case study within a broader
535 context, we conclude that challenges and opportunities to small-scale aquaculture in tropical
536 coastal regions are similar, but to varying degrees. Each country and type of mud crab culture
537 system produce different outcomes in terms of feasibility thus might mislead policy makers as
538 limited studies are available. Furthermore, mean values might misrepresent the variability between
539 individual farms. For support programmes and policy makers to recognise the contribution of mud
540 crab farming, detailed information on production chains and market values are required. In Andhra
541 Pradesh where the rate of abandonment of shrimp farms is high, mud crab farming could be a way

542 of repurposing existing earthen ponds. In other areas before undertaking mud crab farming,
543 especially if considering setting up new farms, it is important to assess all the risks (environmental,
544 social and economic) and not solely rely on benefit-cost analyses. Further interdisciplinary research
545 is necessary to assess the effects of direct and indirect climate change caused mortalities and
546 their impact on the feasibility of crab aquaculture in southeast India and other tropical coastal
547 regions.

548 **Author contributions**

549 EA – Writing-original draft preparation, Visualization, Investigation, Software, Validation. PR –
550 Investigation, Writing-reviewing and editing. RB - Conceptualization, Methodology, Writing-
551 reviewing and editing. LMT – Conceptualization, Funding acquisition, Writing-reviewing and editing.
552 LDR - Conceptualization, Methodology, Writing-reviewing and editing, Validation.

553 **Declaration of competing interest**

554 The authors declare that they have no known competing financial interests or personal
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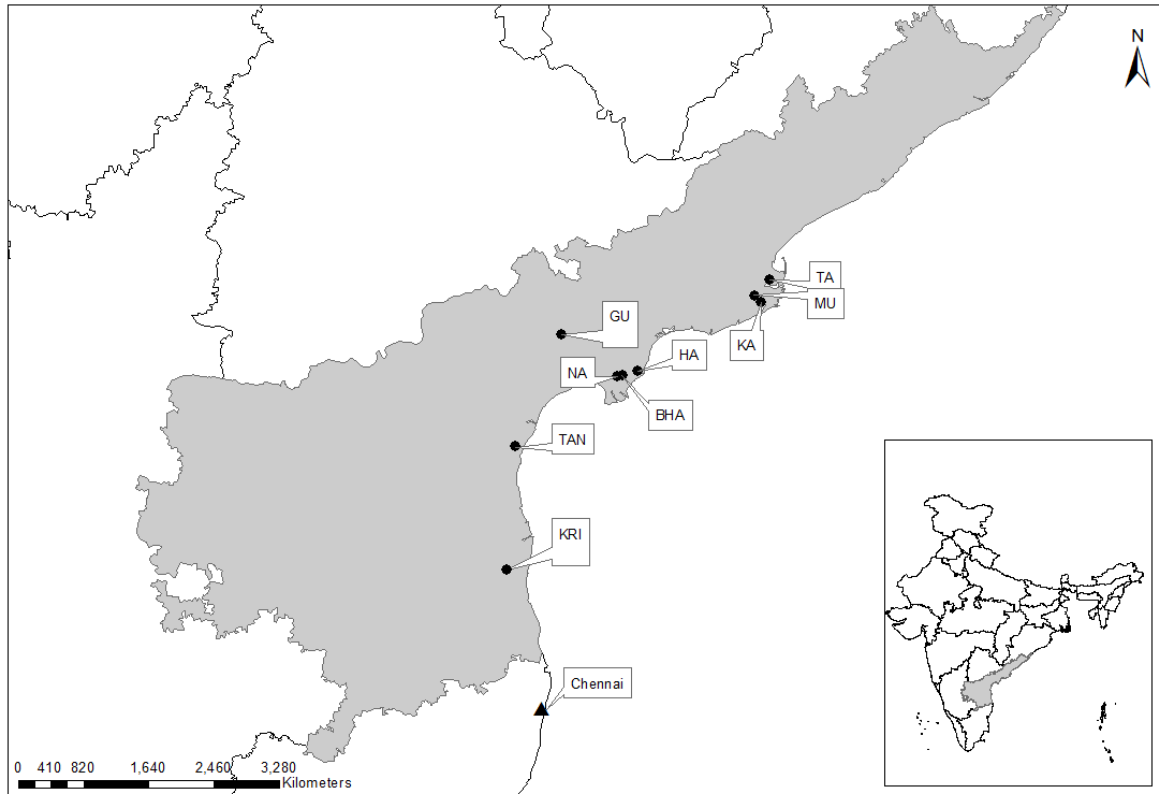
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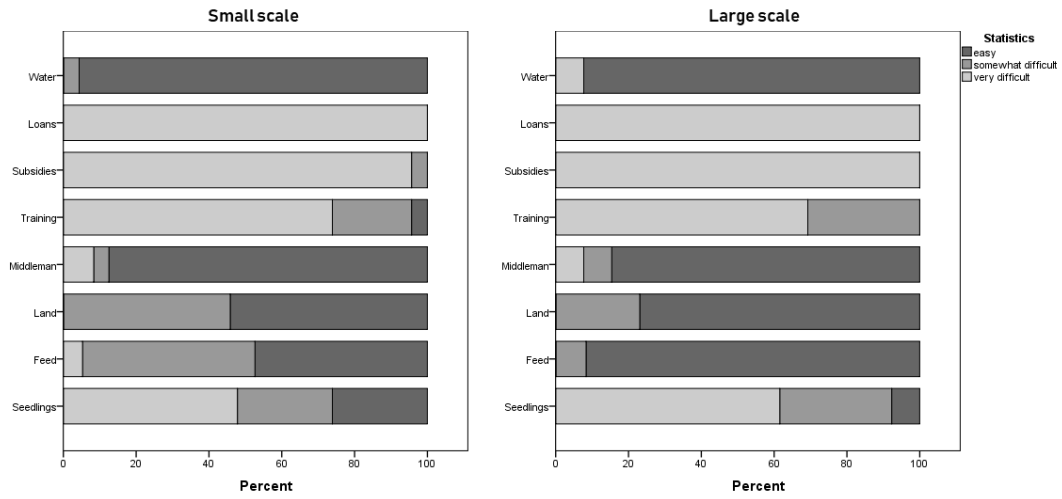
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845 Figure 1. Study sites across Andhra Pradesh – Krishnapatnam (KRI) (n=7), Tangaturu (TAN) (n=1),
846 Guntur (GU) (n=1), Nagaylanka (NA) (n=5), Bhavadevarapalle (BHA) (n=5), Hamsaladeevi (HA)
847 (n=1), Tallarevu (TA) (n=7), Mummidivaram (MU) (n=7) and Katrenikona (KA) (n=3).
848

849 Table 1. Scenarios for benefit-cost analysis. Survival rates differ significantly depending on
850 husbandry practices, quality of stock, stocking density and growth period.

Scenario	Harvest
Scenario 1 – High scenario	45% of stocked crabs harvested every year
Scenario 2 – High/low variable scenario	45% of stocked crabs harvested the first year, 10% stocked crabs harvested next year with the recurring pattern of 45% and 10% every year
Scenario 3 – Medium scenario	23% of stocked crabs harvested every year
Scenario 4 – Medium/low scenario	23% of stocked crabs harvested the first year, 10% stocked crabs harvested next year with the recurring pattern of 23% and 10% every year
Scenario 5 – Low scenario	10% of stocked crabs harvested every year

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854 Figure 2. Perception (%) of mud crab farmers of access to essential items for mud crab farming.

855

856 Table 2. Itemised fixed and variable costs per culture in British Pound (£) for small-scale and large-
 857 scale mud crab farmers. Values are expressed as mean ± standard deviation (SD).

Item	Total costs per culture (£) ^a	
	Small-scale	Large-scale
Fixed costs		
Land lease (n=7, n=5) ^b	366±207	1974±1704
Digging and preparing the pond (n=9, n=5)	218±123	588±557
Fencing (n=12, n=10)	695±384	1500±1843
Variable costs		
Crabs (instars and crablets) (n=24, n=13)	668±654	1213±1000
Feed (n=19, n=12)	765±490	3168±4214
Transportation (n=12, n=4)	209±170	174.±97
Labour (n=23, n=13)	139±117	272±192
Water/electricity (n=8, n=6)	295±103	117±77
Maintenance ^c (n=12, n=8)	195±178	1479±2786
Total costs ^{d, e} as a sum of above indicated individual items	3550	10485
Total costs ^{d, f} indicated by the respondents (n=24, n=13)	2395±928	7568±6645

858 a Indian rupee is equivalent to 0.01039 GBP (10.06.2020)

859 b Indicates sample size for small-scale and large-scale farms, respectively.

860 c Includes watch and ward costs, which is a fixed variable, however was reported as variable maintenance
 861 costs. The proportion was not disclosed.

862 d Total cost = Capital costs + Operational costs

863 e This is the sum of all the items indicated in the table

864 f These total costs were reported by the respondents as their final total costs.

865

866

867 Table 3. Individual profitability indicators– total revenue (TR), net profit (NP), benefit-cost ratio
 868 (BCR) and return on investment (ROI%) for all small and large-scale mud crab farms (excluding
 869 six crab farmers, who had not harvested at the time of interviews and one small scale mud crab
 870 farmer that had not provided information on total profit). The Indian rupee is equivalent to
 871 0.01039 GBP (10.06.2020).

872

Small-scale (n=20)					Large-scale (n=10)				
ID	TR (£)	NP (£)	BCR	ROI%	ID	TR (£)	NP (£)	BCR	ROI%
S1	909	-1429	0.389	-61	L1	3637	-1559	0.700	-30
S2	0	-3324	0	-100	L2	5610	-15432	0.266	-73
S3	327	-1751	0.158	-84	L3	1559	-364	0.811	-19
S4	1455	-810	0.642	-36	L4	2598	1397	2.165	116
S5	468	-425	0.524	-48	L5	1559	-7550	0.171	-83
S6	2057	-2629	0.439	-56	L6	1299	-3398	0.277	-72
S7	0	-2187	0	-100	L7	0	-6368	0	-100
S8	2286	327	1.167	17	L8	312	-13351	0.023	-98
S9	1766	-1901	0.482	-52	L9	0	-446	0	-100
S10	1766	-499	0.780	-22	L10	17922	12223	3.144	214
S11	1766	-499	0.780	-22					
S12	4738	3069	2.839	184					
S13	4738	3304	3.304	230					
S14	4738	3069	2.839	184					
S15	17922	16290	10.983	998					
S16	21507	18530	7.225	622					
S17	0	-4000	0	-100					
S18	1039	-758	0.578	-42					
S19	2857	754	1.359	36					
S20	312	-2390	0.115	-88					

873

874

875 Table 4. Net revenue (NR) and benefit-cost ratio (BCR) for *Scylla* sp. aquaculture in Bangladesh,
 876 Vietnam, Kenya and Tanzania.

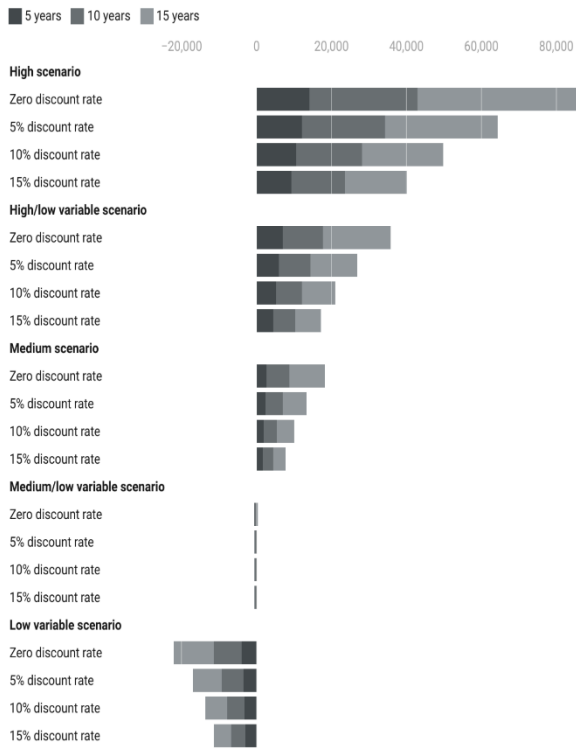
Reference	Country	Species	Type of culture	Number of farms	NR US \$	BCR
Khatun <i>et al</i> (2009)	Bangladesh	<i>Scylla olivacea</i>	Bamboo pens	6 trial blocks	651.28*/ha ⁻¹	1.71
Ferdoushi and Guo (2010)	Bangladesh	<i>Scylla</i> sp.	Fattening in ponds	50	7900.93 / ha ⁻¹	1.94
Basu and Roy (2018)	Bangladesh	<i>Scylla serrata</i>	Grow out in ponds	40	1371.57/ha ⁻¹	1.64
Sujan <i>et al</i> (2021)	Bangladesh	<i>Scylla serrata</i>	Fattening in ponds	75	4418/ ha ⁻¹	1.72
Petersen <i>et al</i> (2013)	Vietnam	<i>Scylla paramamosain</i>	Grow out	80	4700 central Vietnam and 1000 southern Vietnam / per crop	3.55 and 1.97
Moksnes <i>et al</i> (2015a)	Kenya	<i>Scylla serrata</i>	Grow out and cage culture	Trials	226 and - 816/ crop	1.22 and 0.61
Moksnes <i>et al</i> (2015a)	Tanzania	<i>Scylla serrata</i>	Grow out and cage culture	Trials	-211 and - 970/ crop	0.72 and 0.39

877 *average of all trials, NR ranged from -26 US \$ for all male crab culture to 1346.27 for all female
 878 culture and 1018.79 kept in high water level and 330.62 in low water level.

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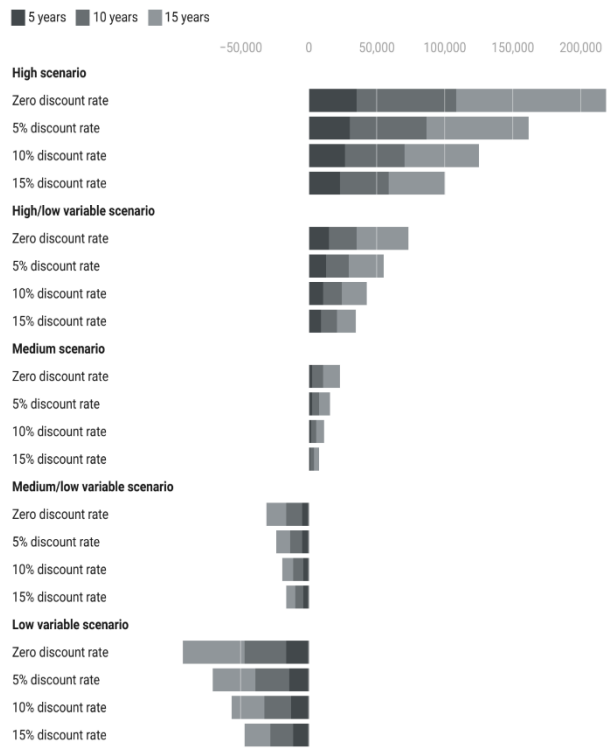
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Small-scale farms



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Large-scale farms



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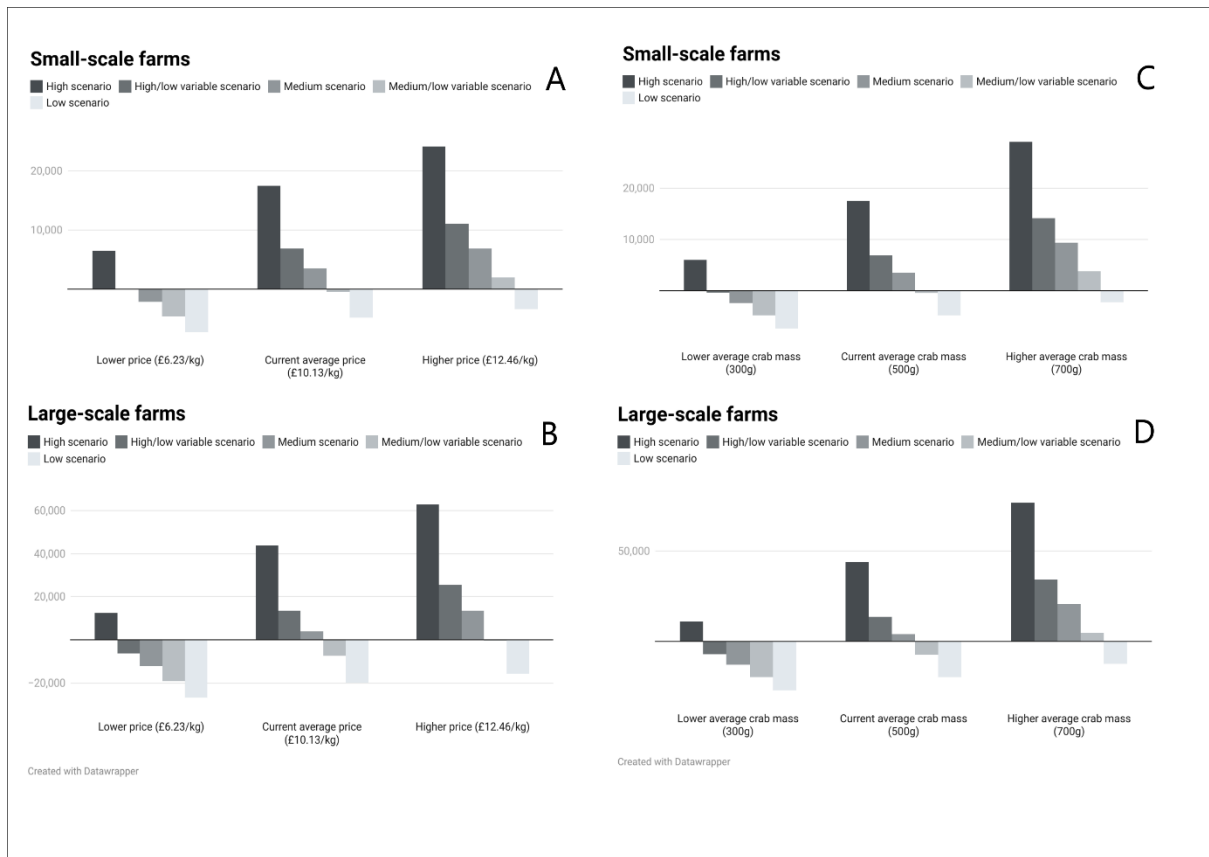
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Figure 3. Net present value (NPV) in British Pound (£) for small- and large-scale farms in five different scenarios with three different discount rates. Indian rupee is equivalent to 0.01039 GBP (10.06.2020).



887

888 Figure 4. Sensitivity analysis to changes in market price per kilogram for small-scale farms (A_
 889 and large-scale farms (B) and changes to crab body mass for small-scale farms (C) and large-
 890 scale farms (D). Calculated for NPV (British Pound £) with a 10% discount rate after 10 years.

891