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# An Interdisciplinary Assessment of the Mud Crab Scylla serrata as a Sustainable Livelihood Resource in Southwest India

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# AN INTERDISCIPLINARY ASSESSMENT OF THE MUD CRAB *SCYLLA SERRATA* AS A SUSTAINABLE LIVELIHOOD RESOURCE IN SOUTHWEST INDIA

by

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in partial fulfilment for the degree of

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# Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee.

Work submitted for this research degree at the University of Plymouth has not formed part of any other degree either at the University of Plymouth or at another establishment.

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# Abstract

**Elina Apine**

**An interdisciplinary assessment of the mud crab *Scylla serrata* as a sustainable livelihood resource in southwest India**

Fishing and aquaculture are important income-generating activities for coastal communities in India. However, the challenges of climate change and overexploitation have prompted the exploration of new, alternative, sustainable, target species that previously have received little attention. This thesis considers the potential of the mud crab *Scylla serrata* as a sustainable livelihood resource for local communities in southwest India where currently crab fishing and, particularly, farming is less common compared to southeast India. As fisheries and aquaculture are inherently complex social-ecological systems affected both by biological and socio-economic factors, this thesis has taken an interdisciplinary approach to identify the main barriers and drivers to small scale mud crab farming in southwest India, in particular, Karnataka.

By applying social science approaches, this thesis revealed that the main barriers to mud crab aquaculture for fishers in Karnataka are poor access to land and lack of financial support. Whereas already established mud crab farmers in Andhra Pradesh on the southeast coast, reported a limited supply of crab seedlings and increased water temperatures causing mass mortality to be their main challenges. Biological studies confirmed the significant adverse effects of ocean warming on mud crabs. Increased water temperatures were linked to decreased microbial diversity of the mud crab gut microbiome, which can potentially affect crab health status. Meanwhile, the location (east or west coast)

and habitat (wild sites or crab farms) did not affect the gut microbial composition. Exposing juvenile crabs to simulated climate change conditions indicated that not only warming, but freshening as a result of projected increased rainfall, causes an increase in oxygen consumption in crabs, potentially negatively affecting their physiological health.

By analysing the overall findings with the help of systems thinking within a social-ecological systems framework, this study identified four key points of intervention, which could improve the sustainable use of this species as a livelihood resource - adaptation to climate change conditions, improved supply of crab seedlings and access to land for aquaculture purposes, and changes in local governance systems.

# Table of Contents

**Acknowledgements** ........................................................................ **i**

**Author's Declaration** ........................................................................ **iii**

**Abstract** ........................................................................ **vii**

**List of Tables** ........................................................................ **xv**

**Chapter one: Introduction** ........................................................................ **1**

1.1.Background ........................................................................ 2
1.2.The biology and ecology of mud crabs ........................................................................ 8

1.2.1.Taxonomic history and morphometric characteristics of *Scylla* species ........................................................................ 8

1.2.2.Life-cycle, growth patterns and habitat choice of *Scylla serrata* ........ 12

1.3.Small-scale mud crab farming ........................................................................ 15
1.4.Case study sites ........................................................................ 18

1.4.1.West coast ........................................................................ 22

1.4.2.East coast ........................................................................ 23

1.5.Thesis aim and objectives ........................................................................ 24
1.6.Analytical framework ........................................................................ 25

1.6.1.Systems theory and systems thinking ........................................................................ 25

1.6.2.Social-ecological system framework ........................................................................ 28

1.7.Thesis outline ........................................................................ 32

**Chapter two: Mud crab as a sustainable livelihood resource for fisher communities** ........................................................................ **37**

2.1.Introduction ........................................................................ 38
2.2.Materials and methods ........................................................................ 41

2.2.1.Study area ........................................................................ 41

2.2.2.Data collection ........................................................................ 43

2.2.3.Data analysis ........................................................................ 44

2.3.Results ........................................................................ 47

2.3.1.Demographics ........................................................................ 47

2.3.2.Application of the sustainable livelihoods approach ........................... 48

2.4.Discussion ........................................................................ 59

2.4.1.Human and social capital and the transforming structures ................59
2.4.2.Natural, physical and financial capital and the transforming structures . ........................................................................................62
2.4.3.Vulnerability context ........................................................................65
2.4.4.Livelihood strategies and outcomes ..................................................67
2.4.5.Institutional context and environmental sustainability ........................69
2.5.Conclusions ..........................................................................................71
**Chapter three: Socio-economic drivers and limitations to mud crab farming as a sustainable small- and medium-scale enterprise ..................73**
3.1.Introduction ..........................................................................................74
3.2.Materials and methods .........................................................................76
3.2.1.Study area and data collection .........................................................76
3.2.2.Data analysis ....................................................................................78
3.3.Results .................................................................................................83
3.3.1.Demographics and characteristics of mud crab farms .......................83
3.3.2.Perceptions of the market, access to support and environmental issues .............................................................................................89
3.3.3.Investment costs and benefit-cost analysis .......................................92
3.3.4.Feasibility assessment of mud crab farming ......................................97
3.4.Discussion ..........................................................................................101
3.4.1.Limitations to mud crab farming .....................................................101
3.4.2.Opportunities and feasibility of mud crab farming ............................107
3.5.Conclusions ........................................................................................110
**Chapter four: Comparative analysis of the intestinal bacterial communities in mud crab *Scylla serrata* in South India .................................................112**
4.1.Introduction ........................................................................................113
4.2. Materials and methods .......................................................................115
4.2.1.Sample collection ...........................................................................115
4.2.2.DNA extraction, PCR amplification and sequencing of 16S rRNA amplicon ..........................................................................................118
4.2.3.Data analysis ..................................................................................119
4.3.Results ..............................................................................................120
4.3.1.The composition of the gut .............................................................120

4.3.2.Phenotypic characterisation of the gut microbiome ........................127

4.4.Discussion ........................................................................................129
4.5.Conclusions ......................................................................................136

**Chapter five: Direct and indirect impacts of climate change on juveniles of the mud crab *Scylla serrata* ......................................................................140**

5.1.Introduction ......................................................................................141
5.2.Materials and methods ......................................................................146

5.2.1.Experimental design and setup ....................................................146

5.2.2. Determination of metabolic rates .................................................149

5.2.3. Data analysis ...............................................................................150

5.3.Results ..............................................................................................151

5.3.1.Survival rates .................................................................................151

5.3.2. Metabolic rates ..............................................................................152

5.4.Discussion ........................................................................................154
5.5.Conclusions ......................................................................................160

**Chapter six: the synthesis ......................................................................162**

6.1.Introduction ......................................................................................163
6.2.Linking social and ecological systems .............................................165

6.2.1.Resource systems and resource units ..........................................169

6.2.2.Social capital, networking and self-organising activities ..................172

6.2.3.Property rights systems and financial support ...............................176

6.2.4.External factors influencing the social-ecological system ................177

6.3.Achieving sustainable aquaculture ...................................................181
6.4.Conclusions ......................................................................................183
6.5.Opportunities for further research ....................................................185

**References..............................................................................................188**

**Appendix 1: Questionnaires ..................................................................248**

**Appendix 2: Detailed information on crab farms ....................................267**

# List of Figures

**Figure 1.1.** Adult Scylla serrata, a) dorsal view; b) ventral view, c) polygonal marks on the swimming leg. Photos by E. Apine, 2019. ..................................10

**Figure 1.2**. Lifecycle of Scylla serrata adapted from Ganesh et al. (2015) and Albert-Hubatsch et al. (2016). ....................................................................13

**Figure 1.3**. Case study states – Karnataka on the west coast and Andhra Pradesh on the east coast. ......................................................................21

**Figure 1.4**. Multitier social-ecological system (SES) framework (adapted from McGinnis and Ostrom, 2014). ..........................................................................30

**Figure 1.5**. Schematic illustration of a thesis outline. .....................................35

**Figure 2.1**. Study sites in Kali, Gangavali, Aghanashini and Sharavati estuaries indicated with triangles and the closest cities – Karwar, Ankola, Kumta and Honnavar indicated with stars. ..........................................................................42

**Figure 2.2**. Modified sustainable livelihood framework based on the framework by the Department for International Development (1999) illustrating a capital pentagon, transforming structures and processes, vulnerability context, livelihood strategies and livelihood outcomes as identified for coastal fisher communities in Uttara Kannada district. ............................................................................54

**Figure 3.1**. Study sites across Andhra Pradesh – Krishnapatnam (KRI) (n=7), Tangaturu (TAN) (n=1), Guntur (GU) (n=1), Nagaylanka (NA) (n=5), Bhavadevarapalle (BHA) (n=5), Hamsaladeevi (HA) (n=1), Tallarevu (TA) (n=7), Mummidivaram (MU) (n=7) and Katrenikona (KA) (n=3). .................................77

**Figure 3.2.** Perception (%) of mud crab farmers of access to essential items for mud crab farming. ...........................................................................88

**Figure 3.3.** Primary, secondary and tertiary sources of income of small- and large-scale mud crab farmers (%). ..................................................................88

Figure **3.4**. Perception of statements (%) of mud crab farmers regarding profitability and stability of mud crab farming and support from various organisations.........................................................................................91

**Figure 3.5**. Sensitivity analysis to changes in (A) market price per kilogram, (B) crab body mass. Calculated for NPV with a 10% discount rate after 10 years. ........................................................................................................................100

**Figure 4.1**. Sampling sites: triangle - wild sites, star – farms. WF – west coast farm, WW – west coast wild site, EF – east coast farm, EW – east coast wild site. Three crabs (C1-C3) were collected from each sampling site. .......................116

**Figure 4.2**. Shade plots of relative abundance of operational taxonomic units OTUs (%) assigned to 20 most abundant genera of individual crab gut microbiomes from 8 different sampling sites. ................................................122

**Figure 4.3**. Shannon's diversity index (H') at the genus level of individual crab gut microbiomes from 8 different sampling sites plotted against the temperature of their sampling sites. .........................................................................125

**Figure 4.4**. Unconstrained hierarchical divisive UNCTREE clusters based on alpha diversity indices of individual crab gut microbiomes at the genus level. Triangles represent east coast samples and squares represent west coast samples. The dendrogram is plotted against an arbitrary equi-stepped scale (A%) in which the divisions sum up to 100...................................................126

**Figure 4.5**. This figure indicates eleven main metabolic processes in which gut bacteria of mud crabs were involved.............................................................128

**Figure 5.1**. Experimental set-up. Each larger tank was assigned to one treatment – ambient, freshening, warming or warming x freshening – and contained four 8L buckets with 16 animals. .........................................................................148

**Figure 5.2.** The mean oxygen consumption of juvenile mud crabs ± SD (confidence interval ±95%) in simulated climate change conditions and microorganism exposure. Three asterisks indicate p≤0.001 between ambient and simulated climate change groups.....................................................................154

**Figure 6.1.** Modified second-and third-tier variables of a social-ecological system framework for small-scale mud crab fisheries and aquaculture in South India identified and discussed in each chapter.. ....................................................167

**Figure 6.2**. Modified social-ecological system (SES) framework (adapted from McGinnis and Ostrom, 2014) with 26 essential attributes of this SES. ...........168

**Figure 6.3.** Flows and attributes of two SES subsystems - crab fisheries (RS1.1) and crab aquaculture (RS1.2). ....................................................................170

**Figure 6.4**. Network structure including crab fisheries, crab aquaculture, government and non-government organisations, and social capital. Grey dotted lines indicate social capital and organisations offering support, identified in chapter two and chapter three. ......................................................................174

**Figure 6.5**. The supply chain of mud crabs with reinforcing feedback loops. The arrow indicates an increase in added value along the supply chain................178

# List of Tables

**Table 1.1**. A selection of morphometric and morphological characteristics of S. serrata, S. tranquebarica, S. olivacea and S. paramamosain adapted from Keenan et al. (1998). ........................................................................................11

**Table 1.2**. Examples of second-tier variables of a social-ecological system (adapted from McGinnis and Ostrom, 2014). ..................................................31

**Table 2.1**. Variables of the SES framework described in this chapter and the corresponding terms. ..........................................................................................45

**Table 2.2.** Criteria for evaluating different types of capital based on the framework by the Department for International Development (1999) and Ellis (2000). ......46

**Table 2.3.** Summary of the key demographics and assets (%) in study sites based on the questionnaire results, excluding focus groups. .....................................48

**Table 3.1.** Scenarios for discounted benefit-cost analysis. ...............................82

**Table 3.2.** Summary of the key attributes of mud crab farmers. .......................87

**Table 4.1** Characteristics of sampling sites and crabs...................................117

**Table 4.2.** The average similarity of OTUs within sampling sites based on Bray-Curtis dissimilarity. .........................................................................................122

**Table 4.3**. Alpha diversity indices for individual animals at the genus level.. ...124

**Table 5.1.** Sample sizes (n) for each analysis conducted on Scylla serrata after 10 d exposure to different simulated climate change conditions and microorganisms..........................................................................................149

**Table 5.2.** Survival rates and average body mass (±SD) for Scylla serrata juveniles after 10 d exposure to different simulated climate change conditions and microorganisms..........................................................................................152

**Table 5.3.** Results of parametric two-way ANCOVA with crab body mass as a covariate of the effects of simulated climate change conditions and microorganism exposure on oxygen consumption (n=100).............................153

# Chapter one: Introduction

## 1.1. Background

Global population growth puts pressure on food security in a world where already 821 million are undernourished (FAO *et al.*, 2019). Fish, crustaceans, bivalves and other aquatic animals are an important source of proteins, fatty acids and micronutrients (Tacon and Metian, 2013; Daviglus *et al.*, 2002; Thilsted, 2012), therefore global fish[1] production (capture fishing and aquaculture) is on the rise, reaching 179 million tonnes in 2018 (FAO, 2020). At the same time, fishing and fishing related activities are important income generating activities in coastal regions, including coastal states of India (World Bank *et al.*, 2012). However, overexploitation of fisheries resources has led to depleted stocks of certain species and full exploitation of others leaving no room for further expansion, negatively affecting coastal communities who depend on these resources for their livelihood and survival, particularly in rural poor regions. Thus, the aquaculture sector is simultaneously growing to meet global demand (FAO, 2016, 2020). Yet, fish farming comes with new challenges both biological and socio-economic. Fish farmers encounter stunted growth, lack of feed, lack of high quality seed (juveniles produced in a hatchery or caught from the wild) and disease outbreaks, however, these challenges are slowly being addressed by technological advances (Bostock *et al.*, 2010; Fujii *et al.*, 2017). Furthermore, adverse influences on the socio-economic conditions of the local fishing communities have been acknowledged (Béné, 2015; Blythe *et al.*, 2015). Many

[1] Unless specified, the term ‘fish’ throughout this thesis includes fish, crustaceans, molluscs and other aquatic animals, but excludes seaweeds and other aquatic plants and aquatic mammals.

communities are under pressure due to the aquaculture associated changes to land use which often means the construction of intensive shrimp aquaculture farms (Gowing *et al.*, 2006). Mangrove forests, rich in biodiversity and acting as nurseries, are particularly affected by this development, and disease outbreaks and pollution have been reported regularly in shrimp farms (Páez-Osuna, 2001).

Global climate change induced by anthropogenic activities is another major factor already adversely impacting people and wildlife. Marine ecosystems are especially vulnerable as climate change as a result of anthropogenically produced and released carbon dioxide ($CO_2$) has caused a rise in sea surface temperature (SST) (Bindoff *et al.*, 2007), a decrease in oceanic pH as a result of this $CO_2$ being absorbed by the oceans ((ocean acidification) (Doney *et al.*, 2009) as well as associated changes such as increased precipitation leading to a decrease in sea surface salinity (SSS) (IPCC, 2014), sea level rise (SLR) (Oppenheimer *et al.*, 2019) and lower oxygen saturation (hypoxia) (Keeling *et al.*, 2010). Each of these factors alone or in combination is causing a number of issues in marine ecosystems such as habitat loss, biodiversity loss, changes in species distribution, coral bleaching, harmful algal blooms and physiological changes in animals (Doney *et al.*, 2012).

In recent decades, marine fish stocks being fished at biologically unsustainable levels have been increasing and in 2017, 34.2% could be classified as overfished (FAO, 2020). Meanwhile, 37 countries have reported increased catch from inland fisheries (contributing 58.7% of global catch), yet for 43 countries no data were available (FAO, 2020). Thus, recognising the rather unpromising state of marine fisheries, the uncertainty of inland fisheries and the widely acknowledged data gap for both marine and inland fisheries, it is important to consider local alternatives to the species with overexploited stocks and/or species associated with negative impacts on the environment (such as shrimp farming). The debate around sustainable fisheries mainly focuses on ecological sustainability in terms of biodiversity conservation (Hilborn *et al.*, 2015). Yet, it can be argued that the other two pillars of sustainability – social and economic sustainability (Purvis *et al.*, 2018) – are equally important, especially for local small-scale fisher communities. One such alternative species is the mud crab *Scylla serrata*.

The portunid mud crab (*Scylla serrata),* also known as the giant mud crab, mangrove crab (e.g., Brown, 1993; Johnson, 2015) or green mud crab (e.g. Department of Fisheries, 2013), is an economically important species in many tropical coastal regions, including India. It is often considered a delicacy and fetches a relatively high price in local and international markets. Mud crab [2] serves as a significant source of income for small-scale fisher communities in these regions as well as a vital protein source (Keenan, 1999). It can be found from the east coast of Africa to Australia and Japan, including oceanic islands such as Fiji and Samoa islands (Keenan *et al.*, 1998). Mud crab fishing and farming in Southeast Asia has been practised for decades, however, farming still often relies on wild caught juveniles despite the recent breakthroughs in commercial *S. serrata* seed production in hatcheries (Quinitio *et al.*, 2001). Fishing for mud crabs usually involves simple gear such as hook and stick, baited lines (Sen and Homechaudhuri, 2017), ring nets and scoop nets with bait

[2] In the Philippines, the name “mud crab” has been replaced by “mangrove crab” due to possible negative connotation of “mud” (Quinitio, Parado-Estepa, & Coloso, 2017), yet in this thesis the name “mud crab” will be used.

(Shanthi, 2009), gillnets and fish corrals (Shelley, 2008). However, increasing demand has been a reason for the decline of mud crab populations in certain areas (Fielder and Allan, 2004). Yet, mud crab farming can be carried out in mangrove incorporated pens that do not damage mangrove ecosystems (Shelley and Lovatelli, 2011). Thus, the existing demand for mud crabs and their economic importance, together with their suitability as a sustainable farming species, make *S. serrata* a prime candidate for investigation as a sustainable livelihood resource in vulnerable coastal regions in India.

Although mud crabs can be found in Indian coastal waters both on the east coast and the west coast, fishing and farming of *S. serrata* is a common activity in particular states, mainly on the east coast, such as Andhra Pradesh, Tamil Nadu and West Bengal with the exception of Kerala, located on the west coast (Marichamy and Rajapackiam, 2001; Thampi Samraj *et al.*, 2015). Meanwhile, in Karnataka located on the west coast, mud crab farming methods have not been widely adopted although it holds the potential for these practices (Marichamy and Rajapackiam, 2001). The barriers to the expansion of mud crab fishing and farming are believed to be the lack of knowledge about mud crab reproductive and developmental biology and disease management (Alberts-Hubatsch *et al.*, 2016) and complex socio-economic constraints (Mirera *et al.*, 2013). Although *S. serrata* is a widely researched species; there is still a lack of knowledge about certain aspects of its biology. No extensive studies have been carried out to identify how changing marine climate drivers such as warming, freshening and acidification of water along with habitat fragmentation, eutrophication and pollution (De Senerpont Domis *et al.*, 2014) might influence mud crabs and especially juveniles that are particularly susceptible to altered conditions (Alberts-Hubatsch *et al.*, 2016). Furthermore, outbreaks of disease in crab farms and hatcheries caused by bacteria and microalgae have already been reported for various crab species, including *Scylla* spp. (e.g. Sulkin *et al*, 2003, Li *et al.*, 2008). The gut microflora plays an essential role in host development and health (Tzeng *et al.*, 2015). Human gut microbiome has been extensively studied, but non-human animals in general, especially, wild animals, have gained less attention (Pascoe *et al.*, 2017). Little is known regarding the gut microbiome of mud crabs, specifically whether there is a geographical variability that could explain differences in the health and hardiness of these crabs. However, technological advances in microbiome sequencing (Srivastav and Suneja, 2019) allow uncovering this complex system quicker and at a lower cost. Such information can inform us further about the functions and mechanisms that require deeper investigation. Therefore, while studies in aquaculture and hatchery settings can determine the impacts of various (often controlled) factors such as oxygen concentration, stock density and cannibalism (uncontrolled) on crab physiology and immunology, gut microbiome studies give more fundamental and equally valuable information. Furthermore, investigating how the gut microbiome responds to any modifications in environment and how these changes, in turn, affect host organism fitness has been identified as one of the one hundred questions in conservation physiology that could be used as evidence to support conservation policies and practice highlighting the ecological relevance of the microbiome (Cooke *et al.*, 2021).

Although training programmes on mud crab farming and financial initiatives are provided by Indian governmental organisations (CIBA, 2018; CMFRI, 2018), small-scale mud crab aquaculture is yet to reach its potential in many areas. Male migration for work purposes has changed the household structure leading to an increased number of female-headed households (Desai and Banerji, 2008) that depending on religion, community and caste often have lower literacy levels (Lingam, 1994). This, however, can influence the household's access to training and financial initiatives as well as increase the risk of being exploited by intermediaries (middlemen) and poachers. Another issue is the complex land tenure system in India and scheduled castes and scheduled tribes, in particular, are in the most unequal situation regarding land ownership (Bakshi, 2008). Scheduled castes and scheduled tribes (SC/ST) are the lowest castes and tribes that have been historically marginalised (Besley *et al.*, 2016), yet the Government of India has developed legislation and schemes to empower SC/ST (Ministry of Social Justice and Empowerment, 2017). While fishers are not affiliated to any particular caste due to their occupation, most fishers in India belong to the other backward caste (OBC) that is described as economically and socially vulnerable (Chauhan, 2008).

Another major obstacle to sustainable mud crab aquaculture is the difficulty to achieve a consistent supply of mud crab seeds produced in hatcheries (Waiho *et al.*, 2018). Natural populations have been under pressure and exploited for seed stocks, resulting in the overfishing of mud crab populations in certain regions (Fielder and Allan, 2004). Despite the breakthrough in seed production and successful establishment of hatcheries, large-scale commercial hatchery production is still limited by low survival rates (Quinitio *et al.*, 2001) and depends on the optimisation of rearing conditions, nutrition and disease management (Nghia *et al.*, 2007).

## 1.2. The biology and ecology of mud crabs

Adult mud crabs are found in muddy estuaries, sheltered coastal areas, brackish water lakes, lagoons and mangrove forests, influenced by tidal waters (Brown, 1993; Le Vay, 2001; Marichamy and Rajapackiam, 2001) in which they often dig burrows (Brown, 1993). Size and colour vary geographically, but commonly *S. serrata* is deep green with a smooth carapace, 15-20 cm in carapace width (CW) and 0.5-1.0 kg in weight (Johnson, 2015) (Fig.1.1.). Juveniles (<30mm CW) and small adult mud crabs (60-99 mm CW) can be characterised as omnivorous, whereas middle- and large-sized crabs are top benthic predators, opportunistic scavengers and exhibit cannibalistic behaviour (Brown, 1993; Thimdee *et al.*, 2001; Alberts-Hubatsch *et al.*, 2016).

### 1.2.1. Taxonomic history and morphometric characteristics of *Scylla* species

The genus *Scylla* de Haan, 1833 (Crustacea: Decapoda: Brachyura: Portunidae) includes four species – *Scylla serrata* (Forskål 1775), *Scylla tranquebarica* (Fabricius 1798), *Scylla olivacea* (Herbst 1796) and *Scylla paramamosain* (Estampador 1949). Due to their morphological plasticity (see Table 1. for details), there has been a longstanding debate regarding the taxonomy. Estampador (1949) divided *Scylla* mud crabs in the Philippines into four species – *S. serrata, S. oceanica* (Dane 1852)*, S. serrata* var. *paramamoisain* and *S. tranquebarica* and such division was agreed by Serene (1952) in Vietnam. However, Stephenson and Campbell (1960) questioned such a division due to the lack of evidence on the effects of wear and tear upon the spinulation of the chelae and the unknown effects of the environment on colouring, and therefore considered only one species – *Scylla serrata* with different morphs.

Current species allocation was carried out by Keenan *et al.* (1998) using molecular methods (allozyme electrophoresis and mitochondrial DNA sequencing (COI and 16s RNA)) in addition to morphometric characterisation. This study eliminated *S. oceanica* (Dane 1852) as a separate species demonstrating that it was a conspecific to *S. serrata* and induced a revision of *Scylla* species based on morphological key features in conjunction with molecular techniques worldwide (e.g., Sarower *et al.*, 2017; Sangthong and Jondeung, 2006; Ma *et al.*, 2006; Ogawa *et al.*, 2012; Trivedi and Vachrajani, 2013; Imai *et al.*, 2004). Recent comprehensive DNA sequence analysis of mud crabs from various sites in India by Balasubramanian *et al.* (2016) has shown that individuals which commonly have been reported as *S. tranquebarica,* are in fact *S. serrata,* and furthermore, *S. olivacea* often had been mistakenly identified as *S. serrata.* In addition, genetic and morphometric studies in Bangladesh have revealed that the most common species in the coastal regions of Bangladesh is *S. olivacea* rather than *S. serrata* as often reported (Rouf *et al.*, 2016; Sarower *et al.*, 2017).

Besides the giant mud crab *S. serrata*, two other species of mud crab *S. olivacea* and *S. tranquebarica* can also be found widely in Indian estuarine waters, but due to the relatively low price they fetch, these crabs are mainly sold in local village markets or used for self-consumption. During this study identification of these species was not carried out therefore they will be referred to as red crabs or *kempedi* in Kannada without specifying the species as *S. olivacea* or *S. tranquebarica.*

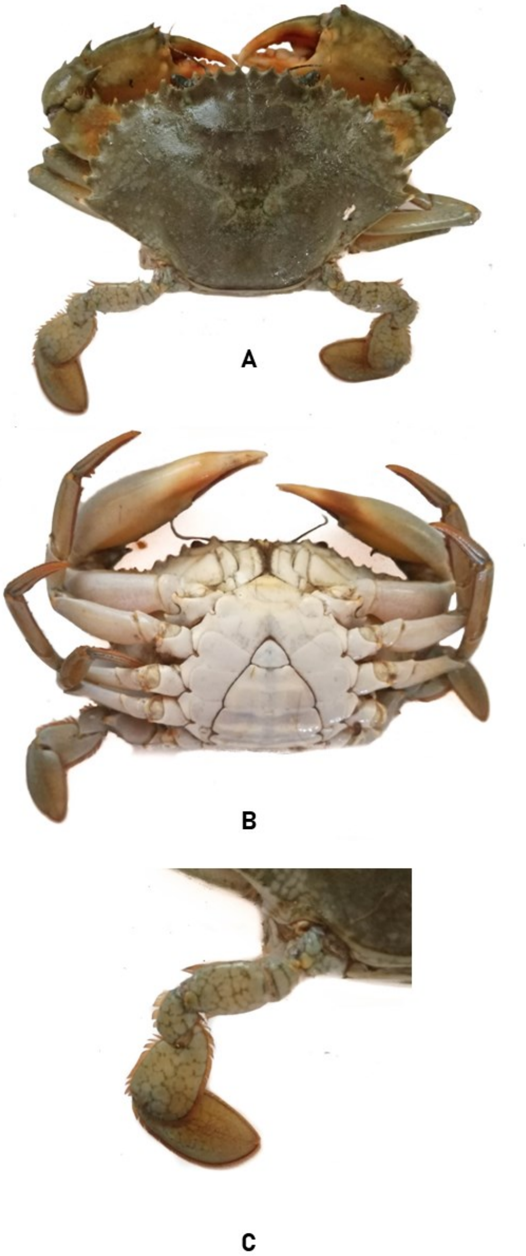


*Figure 1.1. Adult* Scylla serrata*, a) dorsal view; b) ventral view, c) polygonal marks on the swimming leg. Photos by E. Apine, 2019.*

*Table 1.1. A selection of morphometric and morphological characteristics of* S. serrata, S. tranquebarica, S. olivacea *and* S. paramamosain *adapted from Keenan et al. (1998). Morphometric characteristics for morphometric ratios used in species identification: ICS=inner carpus spine, OCS=outer carpus spine, FMSH=frontal median spine height, FW=frontal width, ICW=internal carapace width.*

| **Characteristic** | ***Scylla serrata*** | ***Scylla tranquebarica*** | ***Scylla olivacea*** | ***Scylla paramamosain*** |
|---|---|---|---|---|
| **Colour** | Varies from purple through green to brown/black depending on habitat | Varies from purple through green to brown/black depending on habitat | Varies from red through brown/black depending on habitat | Varies from purple through green to brown/black depending on habitat |
| **Anterolateral carapace** | Spines narrow, outer margin straight or slightly concave | Spines broad, outer margin convex | Spines broad, outer convex | Spines broad, outer margin convex |
| **Carpus of chelipeds** | Two obvious spines on obvious spines on distal half of outer margin | Two obvious spines on obvious spines on distal half of outer margin | One small blunt prominence ventro-medially on outer margin | One small blunt prominence ventro-medially on outer margin |
| **Frontal lobe spines** | High, bluntly pointed with rounded interspaces | Moderately high, blunted with rounded interspaces | Low, rounded with shallow interspaces | High, triangular with angular interspaces |
| **ICS/OCS** | 0.940±0.233 | 0.980±0.251 | 0.006±0.035 | 0.352±0.235 |
| **FMSH/FW** | 0.061±0.010 | 0.043±0.006 | 0.029±0.005 | 0.058±0.012 |
| **FW/ICW** | 0.371±0.016 | 0.412±0.016 | 0.415±0.017 | 0.377±0.007 |

### 1.2.2. Life cycle, growth patterns and habitat choice of *Scylla serrata*

During its life cycle, the giant mud crab migrates from offshore areas with high salinity to muddy estuaries with lower salinity at the juvenile stage and thus can be described as euryhaline (Alberts-Hubatsch *et al.*, 2016). The tolerance to a lower temperature and wider salinity range increases with growth (Baylon, 2010). Mud crabs have five zoeal stages (Z1 to Z5), megalopa (M) and juvenile (C1) before reaching the adult crab stage (Fig.1.2.) (Ganesh *et al.*, 2015; Alberts-Hubatsch *et al.*, 2016). Laboratory experiments by Motoh *et al.* (1977) showed that the zoeal stages take approximately 21 days, while the megalopa stage takes a further 8 to 10 days. Growth occurs through moulting, as for all crustaceans, - the shedding of the exoskeleton, thus the age and growth rate are difficult to assess (Moksnes *et al.*, 2015b). Mud crabs can reach sizes above 200 mm (Alberts-Hubatsch *et al.*, 2016) and the growth is seasonally dependant (Brown, 1993). Sexual maturity depends on geographical location and temperature, however, a study by Prasad and Neelakantan (1989) showed that sexual maturity of *Scylla serrata* females in Karwar, India was attained only after reaching 80 mm carapace width (CW). Mud crabs were the most active at size 120-180 mm CW, yet reproductive activity declined for older animals 190 mm CW.

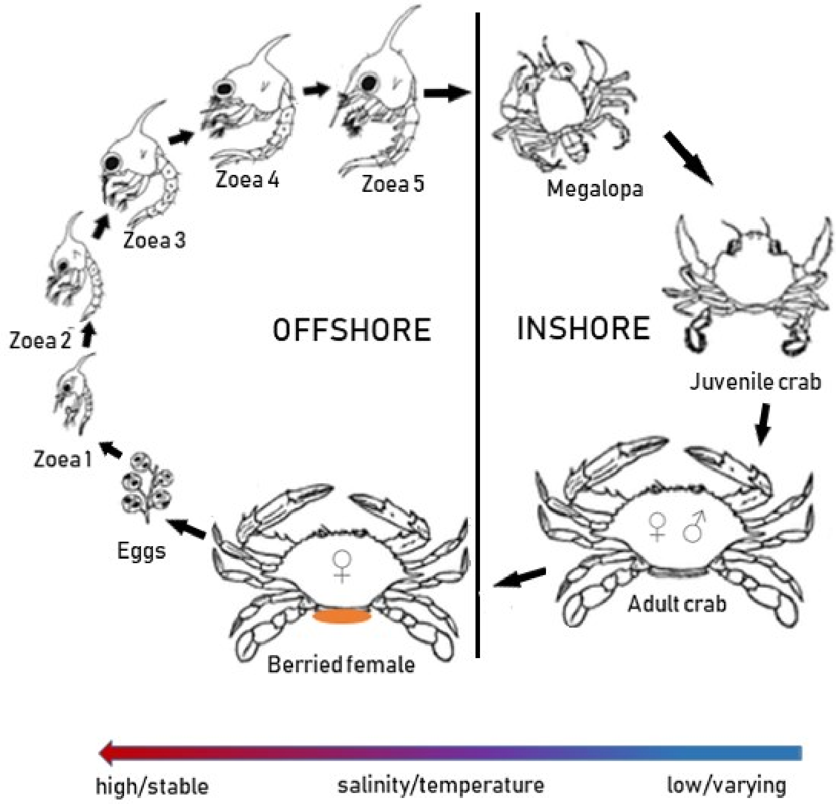


*Figure 1.2. The life cycle of* Scylla serrata *adapted from Ganesh et al. (2015) and Albert-Hubatsch et al. (2016).*

Mud crabs exhibit the behaviour of the 'settle-and-move' model, where larvae settle in on a microhabitat and after metamorphosis, relocate to a different microhabitat (Pittman and McAlpine, 2003). Alberts-Hubatsch *et al.* (2014) propose that such behaviour could be seen as a mechanism to avoid predation and cannibalism. The common assumption is that only juveniles and adult crabs, and not megalopae inhabit estuaries as megalopae rarely have been caught in estuaries (Arriola, 1940). The laboratory experiments showed that mud crab megalopae tend to rise into the estuarine water column during daylight, thus being an easy target for predators (Webley and Connolly, 2007). Therefore, Webley and Connolly (2007) hypothesized that *S. serrata* megalopae settle on the coastal shelf before migrating into estuarine waters in their first crab stage. However, Alberts-Hubatsch *et al.* (2014) in their study in eastern Australia found juveniles more than 7 km upstream, questioning the current hypothesis of megalopae settling in offshore areas, taking into consideration the time required for development from megalopa to juvenile (7-12 days) and pace of movement. Brown (1993) states that in the last stages of zoea, mud crab larvae are transported to estuarine environments by tidal currents, where megalopae settle on suitable substrates. Yet, none of these hypotheses has been proven. Early benthic stage and juvenile crabs have been found in the intertidal zone close to the mangrove fringe (Alberts-Hubatsch *et al.*, 2014). Being an important aquaculture species, the vast majority of studies have focused on the biology of various development stages for the aquaculture industry therefore knowledge of habitat use in the wild remains scarce (Albert-Hubatsch *et al.*, 2016).

Female mud crabs migrate offshore to spawn (Le Vay, 2001) sometimes up to 10-30 km from estuaries (Hill, 1982). The distance migrated however varies depending on the habitat they live in (Hyland, 1984; Le Vay, 2001). Female mud crabs carry between 2 and 5 million eggs, yet patterns of paternity of *Scylla serrata* are not known. Such information is crucial for aquaculture management to avoid inbreeding depression (Kincaid, 1983; Weeks *et al.*, 1999). The efficiency of microsatellites as a tool for parentage assignment, however, has been successfully tested in *Scylla paramamosain* (Xu *et al.*, 2018; Ma *et al.*, 2013).

Besides this long-distance spawning migration, *Scylla serrata* also displays short-scale foraging movements that are also dependant on environmental conditions and the availability of feed (Hill, 1978; Hyland, 1984, Demopoulos *et al.*, 2008).

## 1.3. Small-scale mud crab farming

Mud crab aquaculture has been practised for several decades in the Indo-Pacific region and compared to other aquaculture setups, is often undertaken at relatively low stocking densities (Shelley and Lovatelli, 2011). There are two basic farming methods for mud crabs – 'grow-out' of juveniles and 'fattening' of crabs with low flesh content (Keenan, 1999). Fattening is a process where newly moulted sub-adult crabs (known as "empty crabs" or "water crabs") are fed to grow and fill their new shell (Shelley and Lovatelli, 2011; Keenan, 1999; Marichamy and Rajapackiam, 2001). Grow-out is traditionally done with wild captured juveniles (Keenan, 1999) that are less than 10 g (Moksnes *et al.*, 2015a). Cultivation of mud crabs can be carried out in open (ponds and pens) and closed systems (bamboo cages) (Shelley, 2008).

Mangrove pens are a common mud crab cultivation system in Southeast Asia that has little or no impact on mangrove forests. Therefore, the implementation of sustainable mud crab farming pens incorporated within mangroves has been promoted as a tool for mangrove restoration and conservation (Anilkumar, 2017). These sustainable pens are recommended to be constructed in low- to medium-density mangroves with relatively low tidal ranges (Shelley and Lovatelli, 2011). Pens can be made of a bamboo framework covered with nylon mesh to prevent crabs from escaping and canals are dug to deepen the estuary floor (Triño and Rodriguez, 2002; Primavera *et al.*, 2010) or completely of wood or plant fencing (Shelley and Lovatelli, 2011). Triño & Rodriguez (2002) reported that a higher survival rate was observed in pens with stocking densities of 0.5 crabs per $m^2$ than at 1.5 crabs per $m^2$. Yet even with increased mortality at 1.5 crabs per $m^2$, a high profit was earned at this stocking density and mixed diet, indicating that such an integrated aquaculture method is viable both from an economic and environmental perspective as mangrove trees are kept intact (Triño & Rodriguez, 2002).

Mud crabs, especially when used in 'grow-out', also can be farmed in earthen ponds. Such methods are more common for middle- and large-scale farming as they require the initial preparation of ponds that is more extensive compared to pen systems (Shelley and Lovatelli, 2011). Soil, where ponds are constructed, preferably should be alkaline or prepared through a liming process (Rekha, 2009) as acidic soils have a negative effect on water quality (Wurts and Masser, 2013). Furthermore, acidic soils tend to absorb organic phosphorus while increased pH makes phosphorus more available (Boyd and Pillai, 1985). Phosphorus is a key nutrient required for primary producers (phytoplankton) and it also enhances fish growth (Sugiura, 2018). Ponds usually are rectangular with a depth of 80 to 100 cm with sluice gates, and water exchange should be provided (Rekha, 2009). As mud crabs exhibit cannibalistic behaviour (Alberts-Hubatsch *et al.*, 2016) that affects the survival rate in open farming systems, animals should be kept at relatively low stocking density (Shelley, 2008) and refuge, such as bamboo shelters, seaweed and nets, should be provided (Balasubramanian, 2009, Quinitio *et al.*, 2001). Therefore, a common way of fattening mud crabs is in bamboo or other local timber cages where each animal is kept in an individual cage that is placed in intertidal zones within mangroves (Shipton and Hecht, 2007). However, it has been shown that cage farming is not a sustainable or profitable activity for local communities in East Africa due to the poor growth, survival and profitability, unless it is carried out on a large scale (Moksnes *et al.* 2015a).

As the size of mud crab aquaculture setups (hatcheries and farms) increases, so does the risk of disease. The larvae are particularly susceptible to various bacterial and viral diseases compared to adult crabs (Azra and Ikhwanuddin, 2015; Waiho *et al.*, 2018). While mud crabs are considered to be relatively hardy organisms to various infections (Jithendran *et al.* 2010), there have been outbreaks in China of ‘milky disease’ in *S. paramamoisam* farms caused by parasitic dinoflagellates (Li *et al.*, 2012) and ‘sleeping disease’ in *Scylla spp.* farms caused by the virus (Weng *et al.*, 2007). Therefore, it has become important to report all cases of disease and isolate infected individuals, to prevent the spread of the disease, especially in the natural environment (Lavilla-Pitogo & de la Peña, 2014). Mud crabs can be affected by viral, bacterial and fungal diseases as well as by various infections caused by parasites (Jithendran *et al.*, 2010).

Agriculture has been acknowledged to be one of the biggest contributors to climate change (Lynch *et al.*, 2021), biodiversity loss and habitat destruction (Dudley and Alexander, 2017), therefore unsurprisingly aquaculture as another food production system is also associated with negative environmental impacts, especially if carried out in a large, intensive and uncontrolled way. The aquaculture sector (not identifying particular species) has been linked to eutrophication, harmful algal blooms and hypoxic events (e.g. Chislock *et al.*, 2013; Herath and Satoh, 2015) as well as increased concentrations of pathogenic bacteria and viruses (e.g. Vezzulli *et al.*, 2008) caused by the mismanaged release of nutrients such as nitrogen and phosphorus and solid organic matter. The use of antibiotics in aquaculture can also advance the spread of antibiotic resistant pathogens (e.g., Zou *et al.*, 2011, Cabello *et al.*, 2016) and antibiotic residues (Chen et al, 2020) in receiving waters and aquaculture ponds. Furthermore, as aquaculture is expanding, there are concerns about the use of resources such as water, land and feed and the consequences to local communities (Naylor *et al.*, 2021). The use of wild catch as feed for aquaculture is one of the most controversial aspects. While the adverse impact on land and water use of current mud crab farming practices can be kept to minimal if the mud crab does not become a boom crop (Hall, 2003), having no formulated feed for mud crabs means complete dependency on live fish, which in turn means pressure on fish populations and the competing interests of food security.

## 1.4. Case study sites

India is the sixth and second leading country in marine and inland capture fisheries production, respectively and the second biggest producer of aquaculture species, including inland and marine finfish species, molluscs, crustaceans and aquatic plants constituting 7.1% of the world's total, in 2016 (FAO, 2018). India has vast aquatic resources – 8,118 km long coastline, 1.24 million ha of brackish water, 0.19 million km long rivers and canals and 5.56 million ha of reservoirs, ponds and tanks (Department of Animal Husbandry, Dairying and Fisheries, 2018). At the same time, India's mangrove cover is 4,921 $km^2$ being 45.8% of the total mangrove cover in South Asia and 3.3% of the world's total mangrove cover (Forest Survey of India, 2017). In 2017-2018, fish production in India was 3.56 million tonnes of marine fish and 8.76 million tonnes of inland fish (Department of Animal Husbandry, Dairying and Fisheries, 2018). The value of fish and fisheries products in 2017-2018 for export reached 7.08 billion US dollars (Department of Animal Husbandry, Dairying and Fisheries, 2018a). Although inland fisheries are a prime sector of employment and livelihoods in India, there are well acknowledged gaps in data collection of parameters such as fishing effort and per capita yield (Central Statistics Office, 2011). The fisheries sector engages over 14.5 million people at the primary level and this number is estimated to be even higher along the whole production chain (Department of Animal Husbandry, Dairying and Fisheries, 2019).

Brackish water areas that India is rich with, can be used to cultivate a plethora of species, from shellfish to finfish and seaweed, yet hardly 15% are utilised for this purpose (Department of Animal Husbandry, Dairying and Fisheries, 2019). Brackish water areas are mainly used for shrimp farming that bloomed in the mid-1980s (Nayak, 2017), which however has been associated with disease outbreaks and huge economic losses. Coastal aquaculture in saline and brackish waters, including mud crab farming, is regulated by The Coastal Aquaculture Authority Act 2005 to ensure sustainable aquaculture with minimised harm to the environment and livelihoods of local communities. All brackish water farms have to be licensed and follow guidelines from the Coastal Aquaculture Authority. A person carrying out an unregistered coastal aquaculture enterprise can be punished by imprisonment of up to three years, fined up to 100,000 Indian Rupees (~980 GBP) or both (The Coastal Aquaculture Authority Act, 2005). Meanwhile, there is no specific legislation regulating inland (freshwater and brackish water) crab fishing.

In India, the mud crab *S. serrata* is a brackish water species and has been acknowledged as an important aquaculture species by, for instance, The Marine Products Export Development Authority (MPEDA) and the Central Institute of Brackishwater Aquaculture (CIBA). For this PhD, two states in south India were chosen for conducting research studies: Karnataka on the west coast where mud crab farming has not flourished, and Andhra Pradesh on the east coast, where small- and middle-scale mud crab farming is common activity (Fig.1.3.)

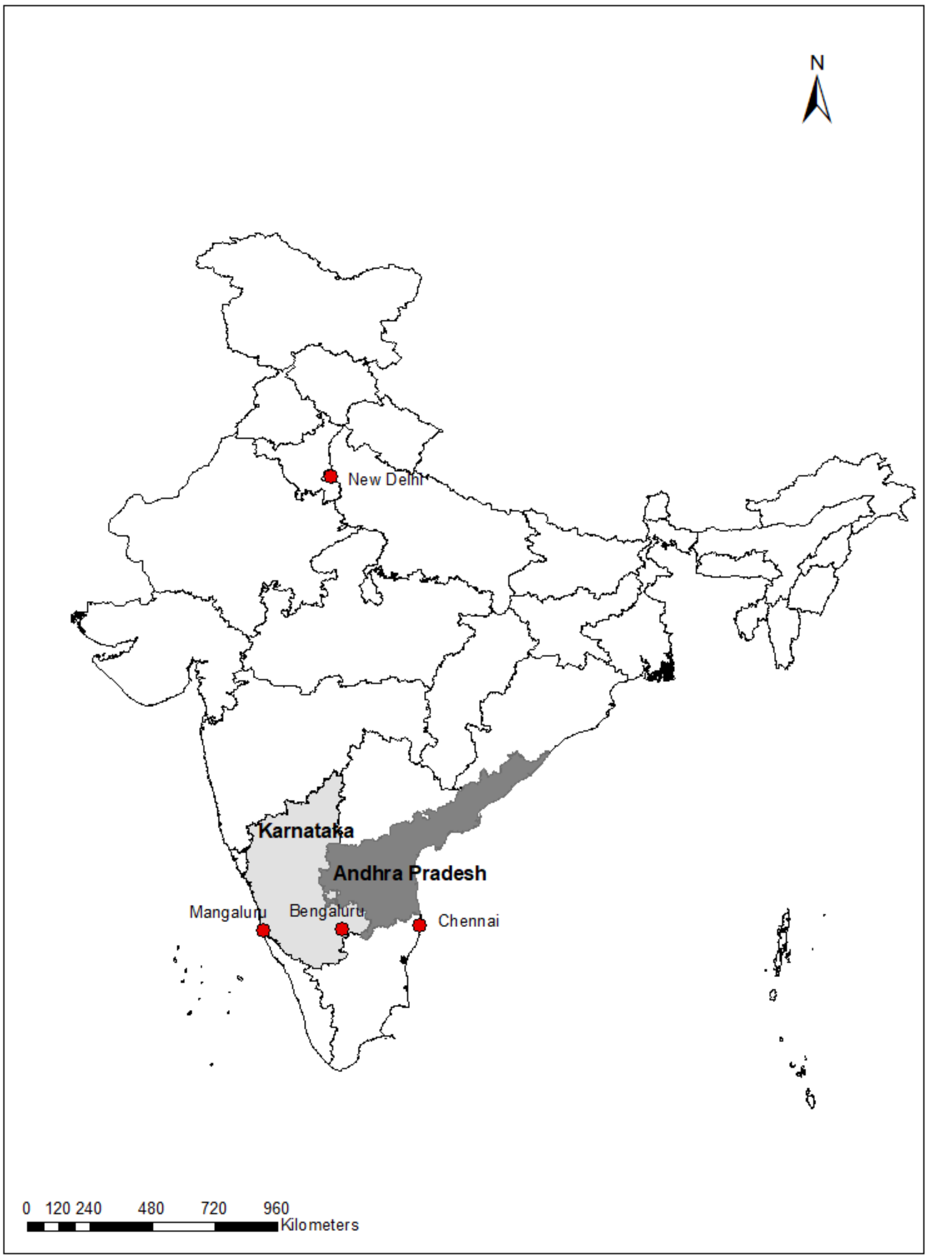


*Figure 1.3. Case study states – Karnataka on the west coast and Andhra Pradesh on the east coast.*

### 1.4.1. West coast

Karnataka has a 360 km long coastline and 8,000 ha of brackish water (Government of Karnataka, 2016). There are several rivers in Karnataka originating from the Western Ghats mountain range that runs broadly parallel with the southwest coast of India. These create a network of estuaries that provide habitat for many commercially important species, e.g., crabs, prawns, bivalves and finfish. The main overall economic sectors in Karnataka are agriculture and the dairy industry (Ministry of Information and Broadcasting, 2018) and the state is in the sixth and fourteenth place in marine fish production and Inland fish production nationally, respectively (Department of Animal Husbandry, Dairying and Fisheries, 2018). Despite having natural resources and apparent potential, Karnataka contributes only 4% to the total fish production in India.

There are no data available exclusively on inland fisher communities in Karnataka, yet regarding marine fishers, it is known that there are 30,713 fisher families in Karnataka of whom 28,533 are considered as traditional fisher families (fishing is their ancestral occupation), 32,037 fishers are involved in full time fishing and 6,657 in part time fishing (CMFRI, 2010). However, based on personal observations, estuarine fishers being in close proximity to the sea tend to be involved in all types of fishing, therefore this data gives approximate estimation not only of marine fishers but also coastal and estuarine fishers. Similarly, there is no information on the number of mud crab farms, but according to the latest data published by the Coastal Aquaculture Authority (2021), there were 48 active brackish water shrimp farms and 39 of them were located in the Uttara Kannada district. In total there is information on 266 more farms that have not renewed their licence as it has to be renewed every five years.

### 1.4.2. East coast

Andhra Pradesh with a 974 km long coastline (Ministry of Information and Broadcasting, 2018) and approximately 150 000 ha of brackish water (Krishnan *et al.*, 2014), is one of the biggest producers of farmed fish nationally in India (Subramanyam and Prasad, 2017; Belton *et al.*, 2017). In 2017-2018 Andhra Pradesh produced 2.86 million tonnes classified as inland fish production, including aquaculture (Department of Animal Husbandry, Dairying and Fisheries, 2018). The rivers Godavari and Krishna that flow through the state are the second longest and the fourth biggest in India, respectively, and are an important source of livelihood for local communities (Kummari *et al.*, 2018). The aquaculture sector in Andhra Pradesh has a long history originating in the late 1950s and advancing in the late 1960s mainly for carp stocking (Belton *et al.*, 2017). Shrimp farming in Andhra Pradesh started in the 1980s and currently, the state contributes more than half of India's shrimp production (Krishnan *et al.*, 2014). Thus, unsurprisingly the total number of brackish water shrimp farms registered since 2007 was 20,232, but only about a quarter (4,641 farms) has renewed their licence and can be considered as currently active (Coastal Aquaculture Authority, 2021). As of January 2021, the majority of the farms, 1,599, are located in the Nellore district.

## 1.5. Thesis aim and objectives

The overarching aim of this thesis is to identify the main socio-economic and biological challenges and opportunities to mud crab fishing and small-scale farming as a sustainable livelihood resource for fisher communities in southwest India, in particular in the state of Karnataka. Chambers and Conway (1992) describe livelihood as sustainable if it 'can cope with and recover from stress and shocks, maintain or enhance its capabilities and assets, and provide sustainable livelihood opportunities for the next generation'. To achieve this, an interdisciplinary approach is applied, combining both social and biological sciences.

Klein and Newell (1996) define interdisciplinary studies as 'a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with by a single discipline or profession'. Local communities and mud crabs are interconnected in a complex social-ecological system, where the socio-economic situation, environmental conditions and mud crab characteristics are equally important, therefore an interdisciplinary approach, combining both biological and social sciences, has been chosen. To assess the suitability of *Scylla serrata* as a sustainable livelihood resource on the west coast of India, it is thus essential to provide and evaluate a holistic overview of both current socio-economic and environmental conditions as well as mud crab suitability in the long term taking into account factors such as climate change.

Therefore, the objectives of this work are to:

1. Determine the perceptions of fisher communities of the mud crab as a sustainable livelihood resource and identify the main socio-economic challenges for undertaking small-scale mud crab farming in southwest India.
2. Evaluate the long term feasibility of already implemented small-scale mud crab farms in southeast India and identify drivers and limitations to small-scale mud crab aquaculture in south India.
3. Identify how geographical location, habitat and environmental factors influence the composition of the mud crab gut microbiome and how that affects crab health status.
4. Assess how direct and indirect climate change parameters affect the physiological responses of juvenile mud crabs.

## 1.6. Analytical framework

In order to meet the thesis aim and objectives, an analytical framework incorporating systems thinking and social-ecological systems framework was adopted.

### 1.6.1. Systems theory and systems thinking

Newell (2001) argues that interdisciplinary research at its core is concerned about complex systems, and fisheries and aquaculture, influenced by a variety of socio-economic, ecological and biological factors, are inherently complex systems (Cordeiro and Sogn-Grundvåg, 2019). A system is a set of interconnected entities with a changing pattern of behaviour and if the system becomes complex with increasing numbers of components that interact with each other in a different way depending on relationships, dependencies and competition (Meadows, 2008; Siegenfeld and Bar-Yam, 2020). Complex systems can adapt, change, respond to events, seek their survival and they are resilient, and often self-organised and self-mending. Recognising that classical reductionist approaches cannot explain the interactions within systems (Vasko, 1988), the shift from classical paradigms toward system theory started in the 1930s (Klir, 1972). The concept of systems theory started with general systems theory (GST) developed by the Austrian biologist Ludwig von Bertalanffy as an attempt to show the connections within science disciplines, such as biology, chemistry and physics (Von Bertalanffy, 1972). Simultaneously, similar shifts in paradigms happened in sociology investigating social systems. The American sociologist Talcott Parsons introduced 'the action theory' and AGIL model, where each sub-system has a role in the system, such as adaptation (A), goal attainment (G), integration (I) and latency (L) (Inglis and Thorpe 2012). However, Parson's ideas were widely criticised, thus alternative systems theory based on some of Parson's ideas was formulated by the German sociologist Niklas Luhmann in the 1980s. Luhmann described society as the social system that comprises of other social systems (e.g. education system, the economy) that are 'autopoietic' – creating their own elements and making themselves constantly anew (Inglis and Thorpe, 2012).

A systems approach is now applied to a variety of disciplines creating such interdisciplinary fields of study as systems ecology, systems chemistry, systems psychology, systems biology and system dynamics. On the contrary to the aforementioned fields of studies, systems thinking can instead be described as a skill set or a tool that is used to understand the behaviours between system entities and predict them and modify them in order to achieve desired effects (Arnold and Wade, 2015). The term ‘systems thinking’ was proposed by Barry Richmond in 1987 and has many different definitions. Yet, all of them acknowledge that systems thinking consists of the following: elements, interconnections and a function or purpose (Meadows, 2008). Changing elements will not significantly affect the system, but changes in the interconnections – how elements feed into and relate to each other, as well as purpose, can lead to greatly altered systems. Another way how to think about and analyse systems is to identify stocks (elements of the system), flows (changes that happen over time and affect stocks), dynamics of stocks and flows (their behaviour over time), dynamic equilibrium and feedback loops (a mechanism that creates a consisted behaviour) (Meadows, 2008). Not all feedback loops are the same, balancing feedback loops, for instance, are concerned with ensuring stability thus can be described as stability- or goal-seeking. Reinforcing feedback loops, however, are amplifying and reinforcing, and can generate more input towards growth or cause huge loss. Besides, Meadows (2008) recognises three main characteristics of any complex system – resilience, self-organisation and hierarchy. Each system also has its own dynamics – behaviour over time. Furthermore, even complex systems can be modified by identifying ‘leverage points’ or points of power that can induce a large shift in systems behaviour.

However, the changes can either lead to a positive contribution or produce the opposite of the desired effect.

Systems thinking is an important analytical tool or framework that can identify and explain the elements and the relations between these elements, and the mechanisms of how they are controlled. However, being universal, it can dismiss some of the aspects that are important to more specialised systems such as social-ecological systems. Thus the findings of this thesis will also be discussed through the lens of the social-ecological system framework, based on systems thinking.

### 1.6.2. Social-ecological system framework

Social-ecological systems (SES), also called human-environment systems, are complex, constantly adapting systems, where humans are part of nature and not separated from it. The concept of social-ecological systems and the first SES framework was introduced by Berkes and Folke (1998), who held a view that the separation of social systems and ecological (natural) systems is artificial, and sustainable and resilient ecosystems and ecosystem management can only be achieved if both of these systems are linked. This SES framework looked at patterns and interactions between ecosystems, people and technology, local knowledge and property rights institutions and their outcomes (Berkes and Folke, 1998). It largely focused on local resource management systems and combining institutional and ecological resilience. Anderies *et al.* (2004) proposed a framework to analyse the robustness of SES from an institutional perspective. The robustness of complex social-ecological systems is not as easily determined compared to engineered systems and requires understanding about what is the role of institutions and which attributes of the institutions will create a more robust SES. This framework recognised four entities – resource, resource users, public infrastructure and public infrastructure providers, and eight links involved in social-ecological systems.

In this thesis, the social-ecological system framework developed by Elinor Ostrom will be used (Ostrom, 2007, 2009). It aims to organise already identified variables in a nested, multitier network and it is based on systems ecology and complex systems science. The main aim of this framework is to analyse the sustainability of an SES and natural resource governance systems (Ostrom, 2007, 2009). It is a diagnostic framework that aims to identify attributes of 1) the resource system (e.g. mud crab fishery), 2) the resource units generated by that system (e.g. mud crabs, water, fish), 3) the actors of that system (previously known as users) and 4) the governance system, that are directly and indirectly affected by interactions resulting in outcomes achieved at a particular place and time (Ostrom, 2007; McGinnis and Ostrom, 2014). The SES framework also accounts for larger social, economic, political and ecological settings in which they are embedded. Thus the SES framework consists of eight main (first-tier) variables (Fig. 1.4), that can further be unpacked into multiple second- and lower-tier variables (Ostrom, 2007, 2009; McGinnis and Ostrom, 2014). The second-tier variables and the combinations between them can significantly alter the interactions and outcomes. Each social-ecological system might have different second-tier variables, but the SES framework states major second-tier variables that have been identified by empirical studies (Ostrom, 2007) (Table 1.2). This

SES framework applies an inherently multidisciplinary approach that acknowledges the complexity of social-ecological systems.

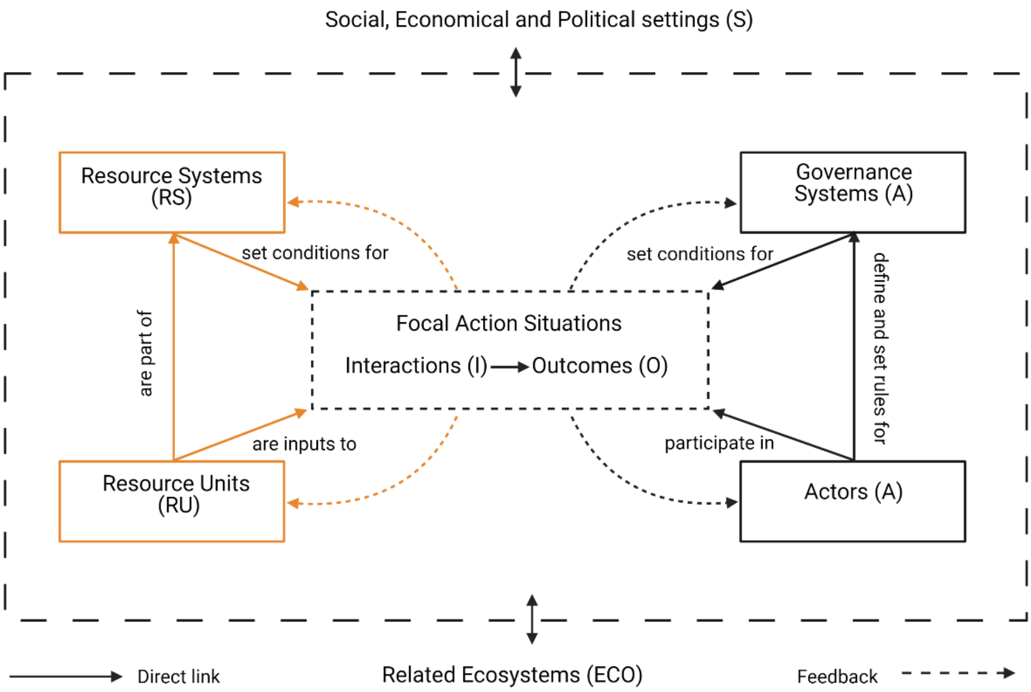


*Figure 1.4. Multitier social-ecological system (SES) framework (adapted from McGinnis and Ostrom, 2014). The dotted line around the exterior indicates that the focal SES is a whole independent system, yet it can be influenced by external factors such as social, economic and political settings and related ecosystems. Solid boxes indicate first-tier components that contain second- and lower-tier variables. Focal action situations in the middle denote where all the action takes place as inputs are transformed by the actions of variables into outcomes. The dotted lines indicate feedback from action situations to first-tier components. Figure created with BioRender.com.*

*Table 1.2. Examples of second-tier variables of a social-ecological system (adapted from McGinnis and Ostrom, 2014).*

<table>
<tr><td colspan="2">Social, economic, and political settings (S)<br>S1 Economic development, S2 Demographic trends, S3 Political stability, S4 Other governance systems, S5 Markets, S6 Media organizations, S7 Technology</td></tr>
<tr><td>Resource systems (RS)<br>RS1 Sector (e.g., water, forests, pasture, fish)<br>RS2 Clarity of system boundaries<br>RS3 Size of the resource system<br>RS4 Human-constructed facilities<br>RS5 Productivity of system<br>RS6 Equilibrium properties<br>RS7 Predictability of system dynamics<br>RS8 Storage characteristics<br>RS9 Location</td><td>Governance systems (GS)<br>GS1 Government organisations<br>GS2 Nongovernment organisations<br>GS3 Network structure<br>GS4 Property-rights systems<br>GS5 Operational-choice rules<br>GS6 Collective-choice rules<br>GS7 Constitutional-choice rules<br>GS8 Monitoring and sanctioning rules</td></tr>
<tr><td>Resource units (RU)<br>RU1 Resource unit mobility<br>RU2 Growth or replacement rate<br>RU3 Interaction among resource units<br>RU4 Economic value<br>RU5 Number of units<br>RU6 Distinctive characteristics<br>RU7 Spatial and temporal distribution</td><td>Actors (A)<br>A1 Number of relevant actors<br>A2 Socioeconomic attributes<br>A3 History or past experiences<br>A4 Location<br>A5 Leadership/entrepreneurship<br>A6 Norms (trust-reciprocity)/social capital<br>A7 Knowledge of SES/mental models<br>A8 Importance of resource (dependence)<br>A9 Technologies available</td></tr>
<tr><td colspan="2">Interactions (I) → Outcomes (O)</td></tr>
<tr><td>I1 Harvesting<br>I2 Information sharing<br>I3 Deliberation processes<br>I4 Conflicts<br>I5 Investment activities<br>I6 Lobbying activities<br>I7 Self-organizing activities<br>I8 Networking activities<br>I9 Monitoring activities<br>I10 Evaluative activities</td><td>O1 Social performance measures (e.g., efficiency, equity, accountability, sustainability)<br>O2 Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability)<br>O3 Externalities to other SESs</td></tr>
<tr><td colspan="2">Related ecosystems (ECO)<br>ECO1 Climate patterns, ECO2 Pollution patterns, ECO3 Flows into and out of focal SES</td></tr>
</table>

The SES framework can be used to analyse interactions and outcomes either at a particular time and place or over time (Ostrom, 2007). This thesis focuses on two resource systems of the same social-ecological system, RS1.1 Small-scale mud crab fisheries and RS1.2 Small- and medium-scale mud crab farming at a single moment in South India, while considering future scenarios. Both resource systems (RS) share the same resource units (RU) and are influenced by the same social, economic, and political settings (S) and related ecosystems (ECO). RS1.2 also partly relies on juvenile crabs obtained from a commercial hatchery but it operates within the same larger context (S). Each RS has its own actors (A), governance systems (GS), interactions (I) and outcomes (O). Although RS1.1 and RS1.2 studied in this thesis are located on the opposite coasts, these case studies are considered as representative of mud crab fisheries in aquaculture in South India and therefore it is assumed that some of the actors (A), governance systems (GS), interactions (I) and outcomes (O) can also overlap. The following chapters identify and describe second-tier variables of the main eight components that are essential to this social-ecological system.

## 1.7. Thesis outline

The thesis is a compendium of four research studies tied with an underlying notion of environmental, economic and social sustainability and analysed through the lens of systems thinking and the social-ecological system (SES) framework. Chapters two to five consist of a brief literature review, materials and methods, results, discussion and conclusions (see Fig.1.5. for a schematic illustration of the thesis outline).

**Chapter two** explores the perception of small-scale mud crab fisheries (RS1.1) as a sustainable livelihood resource in Uttara Kannada in the southwest of India. An additional analytical tool, the sustainable livelihood framework, is applied to identify livelihood assets, livelihood strategies and outcomes and the vulnerability context of local fisher communities and the potential to undertake small-scale mud crab farming.

**Chapter three** discovers drivers and limitations to mud crab aquaculture (RS1.2) in Andhra Pradesh, in southeast India. Discounted benefit-cost analysis reveals potential profit and risks under five different scenarios, thus assessing the economic value (RU4) of the mud crabs.

**Chapter four** compares the gut microbiome of wild and farmed mud crabs from the east and west coasts. This study explores how microbial composition (in terms of bacterial species richness and abundance) and their functions in the gut, are affected by geographical location (east or west coast), type (wild or farmed) and environmental parameters (temperature and salinity), thus influencing health status. In other words, it looks at how the interactions (I) within Resource Systems such as farming in various geographical locations, influence the Resource Units (RU) that consequently can influence the Outcomes (O) in terms of Ecological performance measures (O2) – gut microbial diversity and abundance.

**Chapter five** assesses how climate patterns (ECO1) of Related Ecosystems (ECO) in terms of increased temperature, decreased water salinity and the presence of harmful bacteria influence the ecophysiological susceptibility of *Scylla serrata* juveniles.

**Chapter six** is a synthesis chapter that draws together all four independent studies with the help of systems thinking and the social-ecological system framework identifies which second-tier variables enhance or hinder fishers to rely on mud crabs as a sustainable livelihood resource in southwest India and identifies the main barriers to small-scale aquaculture of mud crabs.

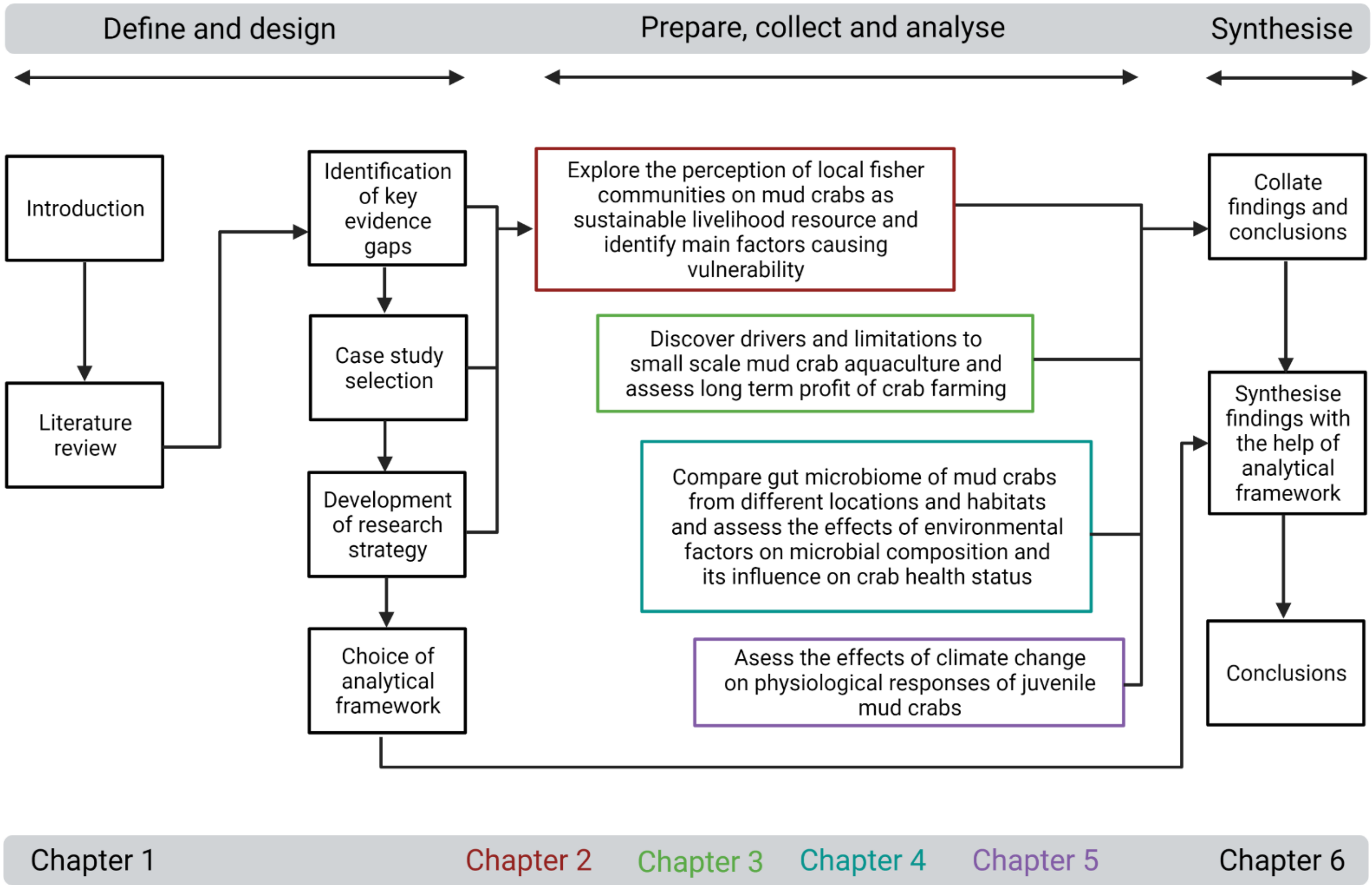


*Figure 1.5. Schematic illustration of a thesis outline.*

# Chapter two: Mud crab as a sustainable livelihood resource for fisher communities

The adapted version of this chapter has been published as Apine, E., Turner, L.M., Rodwell, L.D. and Bhatta, R. (2019). The application of the sustainable livelihood approach to small-scale fisheries: The case of mud crab *Scylla serrata* in South west India. *Ocean and Coastal Management*, 170, pp.17-28, https://doi.org/10.1016/j.ocecoaman.2018.12.024

## 2.1. Introduction

Inland fisheries (including estuaries, mangroves and brackish water ponds) mainly comprise small-scale fishers that are one of the most vulnerable and poorest groups worldwide (Béné, 2009). Small-scale fishers or, as often referred to, artisanal or traditional fishers, can be characterised by often relying completely on fishing and fishing related activities, using simple gear, having local ecological knowledge that is passed down through generations, being involved in skill-intensive fishing activities close to their settlements and often being highly dependent on middlemen (Kurien, 1996). Fishers worldwide face continuous pressure from industrial fishing fleets and inland fishing communities in developing countries and newly industrialised countries such as India can be the most exposed to natural and economic shocks and disasters thus becoming more marginalised and vulnerable (Béné, 2009). Furthermore, the high fishing intensity has led to a significant reduction in marine and coastal fish landings in certain areas (FAO, 2011; Allan *et al.*, 2005). Yet, catch diversification is one of the mechanisms to reduce income variations (Kasperski and Holland, 2013; Robinson *et al.*, 2020). Thus, mud crabs, due to the relatively high price they fetch, are important resource units for small-scale fishers in tropical areas for whom daily catches are unpredictable. Besides, as mud crab hatcheries cannot meet the demand and mud crab farming still partly relies on wild caught crabs (Shelley, 2008), small-scale mud crab fishery can be seen as an important resource system for a wide range of actors As previously mentioned, fisheries are inherently affected by both social and biological factors, therefore assessment of the perception of actors and identification of the main socio-economic variables of this resource system is the most appropriate starting point.

Mud crab aquaculture should not be perceived only as a large-scale commercial activity. Small-scale crab farming, especially grow-out, can offer stability and increase the income as the profit depends on the size of the crabs. Therefore mud crab farming has been identified as a tool for mangrove protection and empowerment of local fisher communities, including women and educated unemployed youth in the state of Maharashtra, India (Anilkumar, 2017). Yet, moving in and out of poverty is a dynamic process that can be influenced by various natural, economic, political factors (Baulch and Hoddinott, 2000). Policy interventions to promote intensive aquaculture can negatively influence fisher communities with no access to land and technologies and minimal education (Hossain *et al.*, 2006). Thus, the promotion and implementation of aquaculture should be done together with assessing and finding sustainable livelihood sources for the most vulnerable communities. To fully assess the interactions and outcomes of this social-ecological system and determine the challenges of undertaking small-scale crab farming, a sustainable livelihood approach is applied. The sustainable livelihood approach is people-centred and has been often used as a practical tool to develop programmes with aims such as poverty reduction or community empowerment, yet it also can be used as a set of principles and as an analytical tool (Farrington, 2001). The approach takes into account four dimensions of sustainability – environmental, social, economic and institutional (Ashley and Carney, 1999). Chambers and Conway (1992) define livelihood as ‘the capabilities, assets (stores, resources, claims and access) and activities required for means of living’ and describe livelihood as sustainable if it ‘can cope with and recover from stress and shocks, maintain or enhance its capabilities and assets, and provide sustainable livelihood opportunities for the next generation’. There are several modifications of the sustainable livelihood approach yet all of them are united by common elements – livelihood resources or assets, mediating or transforming processes, livelihood strategies and sustainable livelihood outcomes (Scoones, 1998; Ashley and Carney, 1999; Department for International Development, 1999; Ellis, 2000). Livelihood assets comprise five types of capital – natural (e.g., land, biological resources), physical (e.g. infrastructure, gear), financial (e.g. incomes, savings, remittances), human (e.g. health and education) and social capital (social ties within the community) (Scoones, 1998; Ellis, 2000). Access to these assets however could be enhanced or hindered by institutions and organisations, in addition to being influenced by seasonality, trends and shocks known as the vulnerability context (Ellis, 2000; Allison and Horemans, 2006). Consequently, taking into account the set of assets possessed and the access mediated by social factors and trends, households adopt particular strategies that are flexible and dynamic (Ellis, 2000).

The sustainable livelihood approach is valuable in small-scale fisheries management as artisanal fisheries are exposed to uncertainty in terms of supply and demand, and fishing activities usually are influenced by social and institutional factors (Allison and Ellis, 2001). However, despite its usefulness and the fact that this approach has been previously used in projects targeting small-scale fisher communities (e.g., Kébé and Muir, 2008; ECFC, 2015; Kébé *et al.*, 2009), it is still not widely applied to small-scale fisheries (Allison and Ellis, 2001; Allison and Horemans, 2006). This study aims to explore the socio-economic factors determining the feasibility of the resource system as perceived by the actors of this social-ecological system in southwest India. Furthermore, by applying the sustainable livelihood approach, capital stocks possessed by fishers, their livelihood strategies and the vulnerability context of local fishers are identified. Consequently contributing to assessing the drivers and limitations for undertaking small-scale mud crab farming by local fisher communities.

## 2.2. Materials and methods

### 2.2.1. Study area

Uttara Kannada is a coastal district located north of Karnataka's chief port city Mangalore (Fig.2.1) with agriculture and fishing as the main economic activities (Bhatta and Bhat, 1998). Uttara Kannada has been reported as having the most marine fishing villages (86 villages) and the largest total fisher population (78,490) in Karnataka (CMFRI, 2010). Mangrove ecosystems, to which mud crab habitats are strongly linked, are found within Uttara Kannada in estuarine complexes of the rivers Aghanashini, Sharavati, Gangavali, Kali and Venkatapur (Sulochanan, 2013) with the four former serving as study sites for the socio-economic study.

The Aghanashini estuary is rich in biodiversity and is highly productive due to the organic material flow from the Western Ghats and mangrove systems (Subash Chandran *et al.*, 2012), and it provides a source of livelihood for thousands of households. Aquaculture practices in the Aghanashini estuary focus on closed watersheds, called *gazani*, which are flood-affected lands of farmers pooled on collective farming arrangements (Bhatta and Bhat, 1998). These watersheds are surrounded by embankments built by the state government in the

1970s and have sluice gates that can be opened and closed to control the water flow in and out of the *gazani* (Bhatta and Bhat, 1998).

The Aghanashini and Gangavali are free-flowing rivers. In comparison, dams have been constructed in the Sharavati and Kali estuaries for hydro-electro power generation. It has been found that two hydro-electro power stations in Sharavati have decreased salinity in the river thus inducing a decline in the fish population (Bhat *et al.*, 2012).

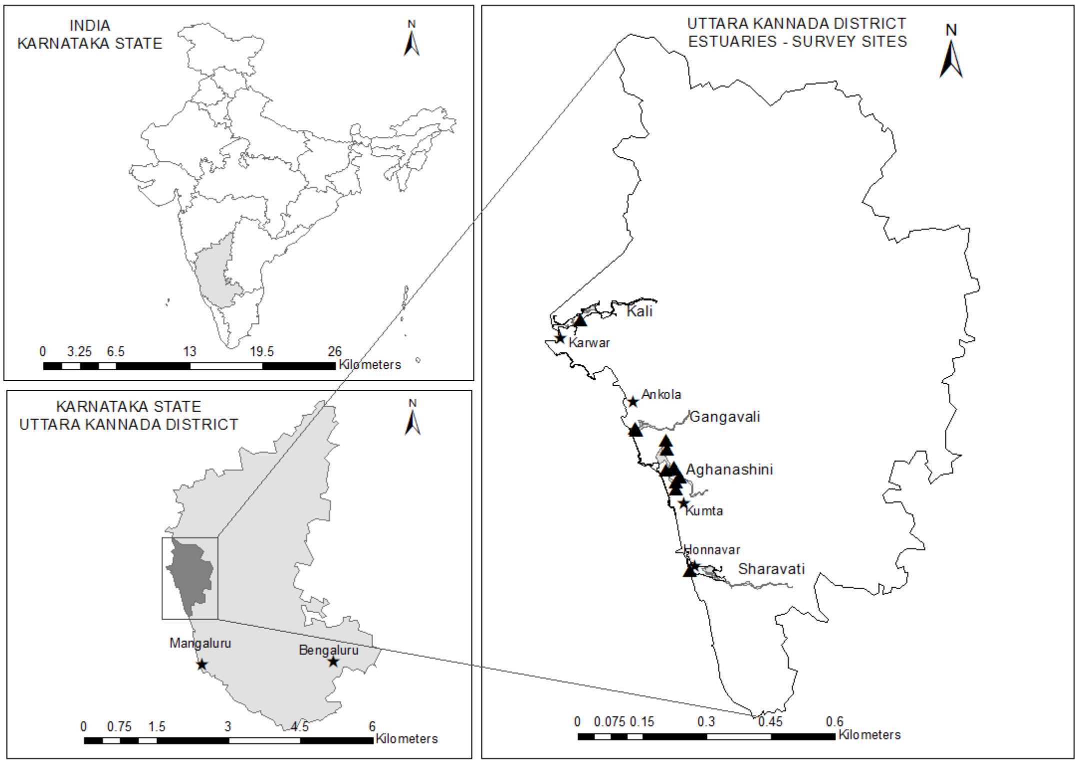


*Figure 2.1. Study sites in Kali, Gangavali, Aghanashini and Sharavati estuaries indicated with triangles and the closest cities – Karwar, Ankola, Kumta and Honnavar indicated with stars.*

### 2.2.2. Data collection

A structured questionnaire was designed to obtain qualitative and quantitative data on fishing activities, in particular mud crab collection as well as social, economic and environmental factors influencing fishers and their daily activities. The questionnaire was divided into five sections – fishing activities, mud crab collection/fishing, mud crab cultivation, shocks and trends, structures and processes (institutions and trust) (Appendix 1). Surveys took place in January and February 2018 in Aghanashini (n=24), Gangavali (n=10) and Sharavati (n=10) estuaries (Fig. 2.1). Respondents were identified by purposive sampling, a sampling strategy that focuses on cases with particular attributes (Aldridge and Levine, 2001), with the help of local interpreters. Surveys were carried out in various areas of these estuaries where mud crab fishing is known to occur. For all individuals fishing was part of their economic activity.

To obtain information from the Kali estuary, a focus group discussion based on the questionnaire was organised (FG Kali). In this specific case, fishers were willing to answer as a group, therefore the focus group consisted of ten respondents. Fishers answered the questions of the questionnaire as a group with five respondents being more active, while the rest agreed or added short statements. Fishers were also given an opportunity to add any information they thought is important. To be able to compare, one focus group discussion of nine respondents was also conducted in the Aghanashani estuary (FG Aghana). In addition, informal semi-structured interviews were conducted with middlemen (n=6) – intermediaries, who purchase crabs from fishers and resell them further. With 69 responses in total and regular repetition of key information in responses, the study was not expanded further due to the indication that the saturation point had been reached (Saunders *et al.*, 2018). Secondary demographic data of Karnataka were used as complementary contextual data.

### 2.2.3. Data analysis

The questionnaire was designed to be analysed by applying the sustainable livelihood approach. While the analysis could begin from any of the components of the sustainable livelihood framework and the Department for International Development (1999) has suggested the vulnerability context as the initial starting point, livelihood resources were considered as the most suitable starting point. Livelihood assets or capitals give people the capability to act and should not only be seen as a 'means through which they make a living; they also give meaning to the person's world' (Bebbington, 1999). Entitlement of the capitals may change over time and each of these types of capitals can transform into other types of capital through transforming processes (Department for International Development, 1999). Unlike Bebbington (1999) who recognised produced, human, natural, social and cultural capital assets, current sustainable livelihood approaches acknowledge human, natural, social, financial and physical capitals. The five capitals in principle identify second-tier variables of the SES framework. For the purposes of clarity, this chapter mainly applies the terminology of the sustainable livelihood approach. However, a reference to the terms of the SES framework will be given where applicable. The variables discussed in this chapter are indicated in Table 2.1.

*Table 2.1. Variables of the SES framework described in this chapter and the corresponding terms.*

| Resource Units | Resource Systems | Governance Systems | Actors |
|---|---|---|---|
| RU5 Number of units → Stock assessment | RS4 Human constructed facilities → Physical capital | GS3 Network structure → Social capital<br>GS4 Property-rights systems → Land ownership/physical capital<br>GS8 Monitoring and sanctioning rules →Restrictions | A2 Socioeconomic attributes → Financial capital<br>A6 Norms (trust-reciprocity)/social capital → Social capital<br>A7 Knowledge of SES/mental models → Local ecological knowledge |

To assess livelihood assets (capitals) possessed by fishers and create a capital pentagon (Department for International Development, 1999), criteria for each type of capital were developed (described in Table 2.2). They were evaluated on a scale from one point (low) to three points (high) for each respondent's assets and recorded a mean score per estuary presented in the results section. Traditional knowledge was considered to be poor if there is a lack of knowledge transfer over generations. Most of the small-scale traditional communities often rely on local ecological knowledge transferred from generation to generation, which gives a significant contribution to natural resource management and conservation programmes (Aswani *et al.*, 2018). Infrastructure was assessed based on whether there are roads and public transport to the local market as well as electricity in the village. Sites with an acknowledged decrease in mud crab catch due to overfishing or other disturbances were identified as depleted natural resource sites that would limit the quantity and diversity of fishers' catch.

Quantitative and qualitative data were analysed using descriptive statistics and graphical analysis using the Statistical Package for Social Scientists (IBM SPSS Statistics 24) and Microsoft Excel 2016. Chi-square tests of independence were carried out to test for statistically significant differences in how often the mud crabs are caught, the perception of changes in mud crab population, and the willingness to undertake mud crab farming depending on location and the level of education. Non-parametric Kruskal Wallis Tests were used to test if there were statistically significant differences between each type of capital and the location.

*Table 2.2. Criteria for evaluating different types of capital based on the framework by the Department for International Development (1999) and Ellis (2000).*

| | **Points** | **Human capital** | **Social capital** | **Natural capital** | **Physical capital** | **Financial capital** |
|---|---|---|---|---|---|---|
| **Criteria** | **1** | Poor traditional knowledge and no skills | Excluded from the community, can rely on the family | Access to depleted natural resources | Poor infrastructure but possess simple gear | No savings and unlikely help from external organisations |
| | **2** | Traditional knowledge and skills | Can rely on the community, possible NGOs and family | Access to natural resources | Good infrastructure and possess various nets | No savings but could get help from fishing societies |
| | **3** | Traditional knowledge and skills + formal education | Member of formal fishing society | Access to natural resources + owns or can access additional land | Good infrastructure + possess various nets + owns a boat | Sufficient savings for investment in gear |

## 2.3. Results

### 2.3.1. Demographics

Uttara Kannada has the largest fisher population in Karnataka constituting 16,236 families of which 89% are below the poverty line (USD 1.90 per day) and 48% do not have any formal education (CMFRI, 2010). The fishers, actors in this resource system, interviewed in our study were both male (68%) and female (32%) of whom 64% were women who were going fishing themselves, while 36% answered on behalf of their husbands. Respondents were from Hindu, Muslim and Christian communities with Kannada, Konkani or Urdu as their mother tongues. The majority of fishers interviewed have been fishing or have been involved in fishing related activities, such as fixing nets since childhood (46%) (Table 2.3) The average age of the respondents from the FG Aghana was 27, while for FG Kali it was 38 with a higher average formal education level.

*Table 2.3. Summary of the key demographics and assets (%) in study sites based on the questionnaire results, excluding focus groups.*

| **Variables** | **% in Aghanashini (n=24)** | **% in Sharavati (n=10)** | **% in Gangavali (n=10)** |
|---|---|---|---|
| Male | 96 | 20 | 50 |
| Female | 4 | 80 | 50 |
| Age class 18-25 years | 4 | nil | 10 |
| Age class 26-40 years | 33 | 20 | 40 |
| Age class 41-65 years | 46 | 80 | 50 |
| Age class over 66 years | 17 | nil | nil |
| Fishing/fishing related activities as the only occupation | 83 | 100 | 100 |
| Involved in sea fishing | 25 | 80 | 80 |
| Catch mud crabs often but irregularly | 54 | 80 | 30 |
| Catch mud crabs rarely | 42 | 10 | 60 |
| Never catch mud crabs | nil | 10 | 10 |
| Retain mud crabs for self-consumption | 83 | 70 | 70 |
| **Share from mud crabs contributing to total income** | | | |
| Only for self-consumption | 13 | 10 | nil |
| Up to 10% | nil | 40 | 80 |
| Up to 25% | 58 | 40 | 10 |
| 25-50% | 29 | nil | nil |

### 2.3.2. Application of the sustainable livelihoods approach

Based on the questionnaire all elements of the sustainable livelihood framework – livelihood assets, transforming structures and processes, vulnerability context and livelihood strategies and outcomes – were identified, and modified according to the conditions of Uttara Kannada. The capital pentagon illustrates the level of five types of capital in each of the four study sites. Each type of capital (natural, social, financial, physical and human capital) was evaluated based on our developed criteria (Table 2.1) for each respondent and focus groups on a scale from one to three and counted the mean score (Table 2.4) for each estuary.

*Table 2.4. The average score of human, social, natural, physical and financial capital for Aghanashini (n=24 and FG Aghana), Sharavati (n=10), Gangavali (n=10) and Kali (FG Kali) estuaries with standard deviation (±SD) where applicable. No variation was observed for Kali estuary as the score is per focus group and for other study locations. The capitals were not assessed by respondents themselves but based on the results to corresponding questions. Kruskall-Wallis test applied to test whether the location affects the level of capitals indicated that there is a statistically significant difference only between location and financial capital.*

| **Estuary** | **Human capital (p=0.666)** | **Social capital (p=0.012)** | **Natural capital (p=0.308)** | **Physical capital (p=0.002)** | **Financial capital (p=0.018)** |
|---|---|---|---|---|---|
| **Aghanashini** | 2.76±0.435 | 2.58±0.503 | 2.16±0.374 | 2.44±0.506 | 1.72±0.541 |
| **Sharavati** | 2.6±0.516 | 3±0.00 | 2±0.00 | 2.2±0.421 | 2±0.00 |
| **Gangavali** | 2.8±0.421 | 3±0.00 | 2±0.00 | 3±0.00 | 2±0.00 |
| **Kali** | 3±0.00 | 3±0.00 | 2±0.00 | 3±0.00 | 3±0.00 |

- *Livelihood assets possessed by fishers in Uttara Kannada district*

The capital pentagon (Fig.2.2) illustrates the level of five types of capital in each of the four study sites. Local communities in Aghanashini, Sharavati and Gangavali estuaries, in general, had a medium and high level of capitals, meaning that the natural resources (mud crabs, fish stocks) are not depleted, the majority of fishers have received formal education and are members of fishing societies. Physical capital varied in each site as, for instance, in Sharavati estuary fishers did not own boats but were mainly employees on marine boats or were fishing from the coast. Kali estuary showed the highest levels of each capital as the members of the focus group were all part of a community group that deposited money in a bank, shared two boats and considered mud crab farming.

The results demonstrated that all fishers had a relatively high level of human capital consisting of skills, knowledge and abilities (Ellis, 2000) and social capital comprising norms and networks (Woolcock, 1998). To identify human capital, we looked at the education level and how it affects decisions on utilising other types of capitals. However, quantification of human capital is not fully possible as traditional or local ecological knowledge would not always be considered, and skills and knowledge are highly variable for each individual (Son, 2012). The majority of fishers based on the survey had primary and middle-school education (up to age 14) (27% and 23%, respectively) and 23% had no formal education.

The assessment of social capital was carried out by asking whether fishers are part of any formal fishing society with informal conversations revealing how equal they felt both within and amongst communities. All fishers from Kali, Sharavati and Gangavali estuaries were a member of formal fishing societies, while 42% of fishers from Aghanashini estuary as well as all the respondents of FG Aghana were not members. Fishers who were not involved in any formal fishing societies or groups considered themselves as true estuarine fishers and saw fishing societies oriented towards marine fishers. They hold a position that they would not get any external help as inland fisheries are not considered profitable and therefore could only rely on themselves and their family. Furthermore, respondents of FG Aghana were not members of any fishing society as they reported they do not have time for participating in meetings. Therefore, they were not eligible to obtain any support from a fishing society, and they also felt they were in an unequal position compared to other fishing communities which are members of fishing societies. However, fishers of FG Kali had also established their own ‘self-help group’ with the aim to deposit money at the bank that could be used for petrol and other expenses. They also carried out fishing in pairs as one had to operate the boat, showing a high level of cooperation within the community.

The assessment of financial capital was difficult as fishers would not disclose whether they have savings and how much. Therefore, our assessment is based on observation and information regarding fishing societies. This analysis shows that due to the ‘self-group’ fishers from the Kali estuary have the highest level of financial capital while Aghanashini has the lowest. More than two thirds (71%) stated that mud crab collection is profitable but unstable due to the unpredictable catch. The share from the giant mud crab contributing to the total household income was up to 25% or even less, up to 10%, for most fishers. Only two respondents reported it to reach up to 50% of the total income.

The natural capital can be assessed by disclosing land ownership and access to natural resources. The majority of fishers do not possess any land other than their homestead land and would not be able to access additional land, therefore showing low levels of natural capital in general. Only 3 out of 44 fishers (7%), all from the Aghanashini estuary leased a *gazani* land or closed watersheds, which are flood-affected lands of farmers who pooled them on collective farming arrangements (Bhatta and Bhat, 1998). Originally they were used for growing salt resistant rice variety in the rainy season and as farming systems for marine fish and crustacean species in the dry season. These watersheds are surrounded by embankments built by the government in the 1970s and have sluice gates that allow control of water flow in and out of the *gazani* (Bhatta and Bhat, 1998). Fishers from other estuaries were aware of such watersheds but they were not common elsewhere. These lands are usually auctioned every five years and the person who receives the leasing rights (usually referred to as the contractor) sub-leases the land to fishers or farmers that are considered as partners. As these used to be farmlands, in most cases the contractor is from the agricultural community. Yet, not in all cases contractors are using the *gazani* ponds themselves. The total area of *gazani* lands leased varied from 20 to 60 acres with 9 to 73 partners (Table 2.5). Small repairs of embankments or sluice gates are done by the users but significant repairs are provided by the contractor. One respondent said that he would not describe aquaculture in *gazani* as a profitable activity due to the high lease rate. Around 30% of the catch in his *gazani* were *Scylla* sp. crabs, and the rest were miscellaneous fish and crustacean species. In some *gazani*, fishers who leased were fully entitled to all their catch and were responsible to sell it themselves, while the practice for the contractor to collect the fishes caught daily and sell them to agents or in the market was also common in some *gazani* lands, sharing the profit among the *gazani* land users.

The physical capital of fishers was evaluated based on boats and gear possessed. Fishers used a wide variety of nets for all types of fish such as throw nets known as *bisu balee*, disco nets, gillnets, circular nets, big and smaller nets with various mesh sizes. Crabs were caught either in these fishing nets or with special nets with mesh size 42 mm or 66 mm or with small ring nets with chicken waste bait. Informal conversations with fishers acknowledged that the infrastructure to village markets and middlemen is well organised. Almost half of the fishers interviewed for the survey owned a boat. Yet, while each of FG Kali respondents possessed their own non-mechanised boat and one also had an outboard motor; none of the respondents of FG Aghana owned a boat.

*Table 2.5. Information on gazani land area and lease rate as reported by fishers. Exchange rate 1£ = 0.01099 INR (20.02.2018).*

| **Variables** | ***Gazani* 1**[a] | ***Gazani 2***[a] | ***Gazani* 3** | ***Gazani* 4** |
|---|---|---|---|---|
| Total area (acres) | 60 | 20 | 40 | 40 |
| Area leased (acres) | 1.6 | 2.3 | 2 | 40 |
| Number of partners | 23 | 9 | n/a | 73 |
| Amount of lease for the whole *gazani* (£/year) | 2198 | 1978 | n/a[b] | 8956 |
| Amount paid by the contractor (£/year) | n/a | n/a | 66 | n/a |

[a] leased by the same respondent
[b] this respondent did not pay a lease but instead was giving all of the catch to the contractor in exchange for a fixed amount

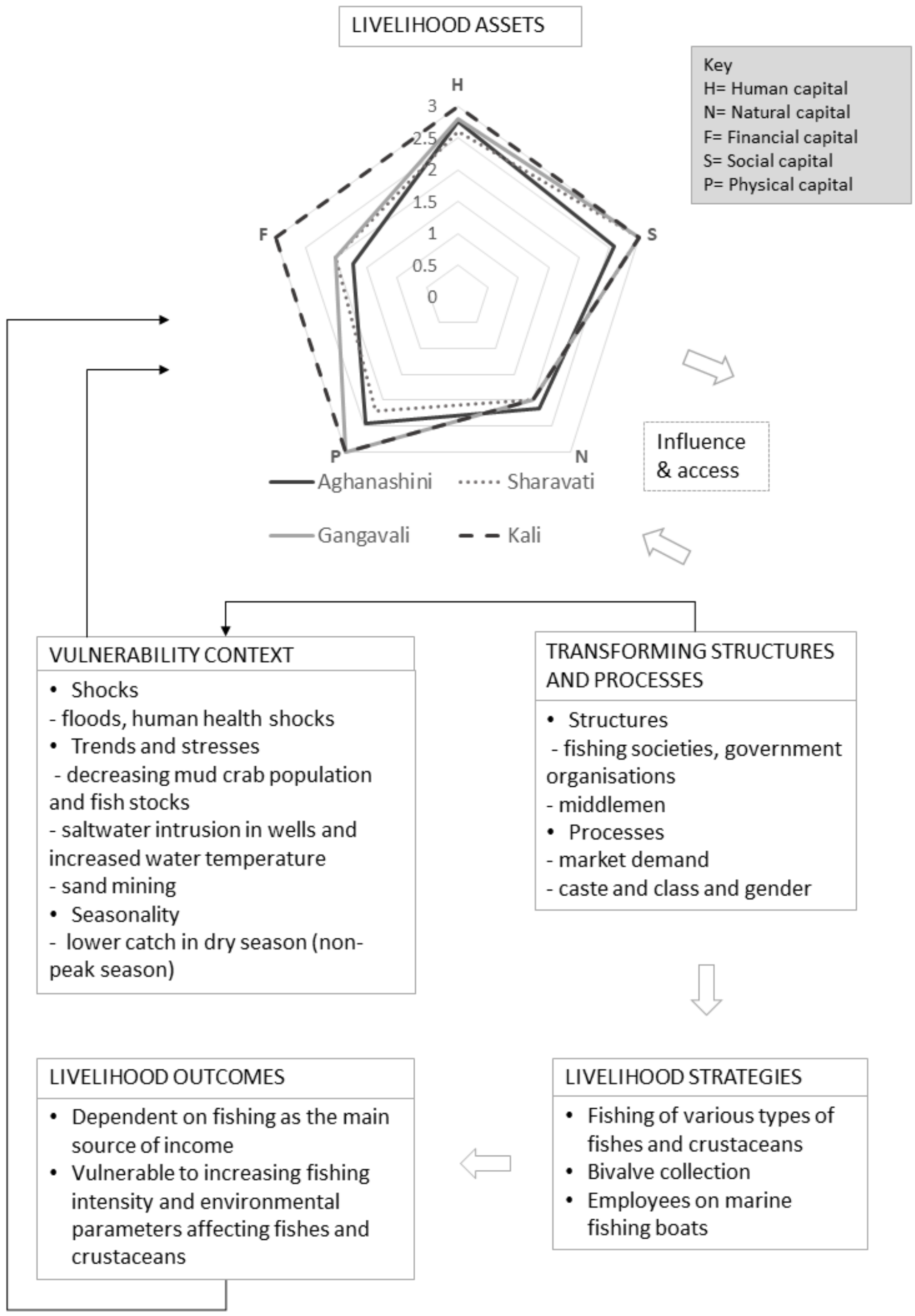


*Figure 2.2. Modified sustainable livelihood framework based on the framework by the Department for International Development (1999) illustrating a capital pentagon, transforming structures and processes, vulnerability context, livelihood strategies and livelihood outcomes as identified for coastal fisher communities in Uttara Kannada district.*

- *Transforming processes and structures in Uttara Kannada*

Access to livelihood assets can be enhanced or hindered by governance systems (organisations and institutions) that act as transforming processes and structures. Fishing societies, described in the previous section, were identified as the main structures due to their influence on social capital, government organisations and middlemen. Based on the informal interviews, government organisations have not intervened significantly in processes, yet middlemen who are purchasing mud crabs from fishers and further resell them to export agencies or hotels. Giant mud crabs were mainly sold to middlemen while red crabs were sold to a local village market. Results show that 55% of respondents would sell crabs, the majority of which are *S. serrata* to a middleman only, while 9% would sell *S. serrata* to a middleman and other *Scylla* crabs in a market. Prices reported by fishers and middlemen reflected varying quality and size of mud crabs (Table 2.6).

Three agents reported selling mud crabs to Chennai, Mumbai, Kolkata, Bangalore or Goa from where they are further sold for export to Singapore, Malaysia and other countries mainly in Southeast Asia. However, besides acknowledged demand from Southeast Asia, there is also demand from hotels in India, particularly in the state of Goa, which is an established local and foreign tourist destination. Two middlemen purchasing crabs from fishers in Aghanashini and Sharavati estuaries were selling the mud crabs to the middleman in Karwar (the closest city) and thus receiving the least profit compared to other middlemen interviewed. The middleman in Karwar owns a shop that serves as a purchase/selling point and he is the only middleman in the city for estuarine fish and crustaceans. He also resells to Chennai, Mumbai or Kolkata for export purposes. Although the quantity of crabs caught by fishers fluctuates daily and seasonally, middlemen recognised that they are able to send relatively stable amounts of giant mud crabs daily by bus for further sale. The average amount sold is approximately 150 kg per month. This could increase up to 400 kg in the rainy season.

*Table 2.6. Quality classes of giant mud crab with description and the average price reported by fishers and middlemen interviewed in 2018. Exchange rate 1£ = 0.01099 INR (20.02.2018).*

| **Quality class** | **1$^{st}$ quality (XL)** | **1$^{st}$ quality (big)** | **2$^{nd}$ quality** | **3$^{rd}$ quality** |
|---|---|---|---|---|
| **Description** | >800g | 550-800g intact | 250-350g intact or newly moulted ('water') crabs | any size with physical damage such as lost limb |
| **Average price (Indian Rupees)** | 10.99-13.18 £/kg | 3.30-5.50 £/kg | 2.75-3.30 £/kg | 3.30 £/kg |

- *Vulnerability context of Uttara Kannada fisher families*

Various processes, whether they are lasting trends or sudden shocks, can have significant influences on fisher communities. One such trend is the evident decrease in the giant mud crab population which the majority of fishers have noticed over the last years 20 years. Fishers were asked to reflect on what has happened to the mud crab population since they started fishing. Of 71% who have noticed a decline, 45% of respondents considered this decline as significant. However, 23% believed that the population level remains unchanged. There is a significant difference between location and these perceptions (p=0.042). In the Gangavali estuary, 70% of fishers answered that the mud crab population has significantly decreased, while a significant decrease in Aghanashini and Sharavati estuaries was reported by only 33% and 50%, respectively. However, 42% of fishers in Aghanashini report a decrease but claimed it was not extreme.

Although 43% of respondents could not state any reason for the decline, more than half had some explanations. Approximately one third of respondents (30%) thought the decline was due to high fishing intensity. One fisherman recalled that 30 years ago there was a good population of mud crabs in the Aghanashini estuary. Another fisherman remembers seeing mud crab burrows that are not common to see anymore. Some fishers also recall that fishers used to catch mud crabs only during the monsoon but now they are collected throughout the year. Others explained the decrease by seasonal changes, tidal changes, oil spills, catching of juveniles and berried female crabs, increasing water temperature, a decrease in the river depth and the absence of tiger prawns in rivers.

Fishers were asked to reflect on whether various environmental, social and industrial factors have any impact on their daily lives. More than half (55%) were not aware of any environmental factors of related ecosystems and claimed they were not feeling any effect. Only 7% and 2% of fishers reported that water pollution and increased water temperature, respectively, significantly negatively influenced their daily life and fishing activities. Yet 11% of respondents acknowledged mangrove expansion as a positive and significant trend due to their role as nursery habitats. Two thirds of respondents (66%) claimed that interactions with other factors such as sand mining, industrial fishing and fishing intensity were strong influences. The fishing intensity was considered as a significant impact negatively influencing their livelihoods by 39% of respondents. Sand mining was recognised as a serious problem only by fishers from the Aghanashini estuary.

- *Livelihood strategies and current outcomes of Uttara Kannada fisher families*

Fishers in Uttara Kannada are involved in fishing various types of fishes and crustaceans as well as in bivalve collection, specifically in the Aghanashini estuary. The giant mud crab is often but irregularly caught by 55% of total respondents and there was no significant difference between location and frequency of catching mud crabs ($p=0.173$). Answers regarding patterns and habits of mud crab collection revealed that there is no consistent pattern regarding how often they go fishing per week or month as it is seasonally dependent. The majority of fishers (61%) identified the rainy season which lasts from June to September as the peak season for mud crab collection while 11% recognised the pre-monsoon season, January to May, as the peak season. The number of crabs caught varied significantly within and between seasons. For instance, one of the fishermen interviewed reported that he had not caught any giant mud crabs for 15 days. By comparison, a different situation is seen with red mud crabs which were reported to be caught more regularly.

Asked whether they know about mud crab farming approaches such as grow-out or fattening systems, 77% replied positively although 15% of them considered gazani lands (several hectares) as suitable for mud crab farming and did not think of small ponds or pens (typically 250 to 2,000 m2). The vast majority (71%) however would not consider undertaking such activity. The key reasons given for not being willing to undertake mud crab farming were lack of land and financial resources with other reasons given including lack of time, knowledge and willingness. Those 9% who would consider undertaking such an enterprise would be encouraged by initial financial support and if the land was made available. Focus group discussions showed that fishers from Kali estuary were aware of mud crab farming techniques and expressed an interest in undertaking such activity, while fishers from Aghanashini estuary had no knowledge about farming possibilities for mud crabs.

## 2.4. Discussion

### 2.4.1. Human and social capital and the transforming structures

Human capital comprises skills, abilities and knowledge in the formal understanding of education and health of labour of the household (Ellis, 2000). Sen (1997) argues that a higher level of human capital also increases the human capability of exploiting other types of capital that goes beyond a singular understanding of the human capital. Although no significant difference in responses to the survey between formal education level and a willingness to undertake mud crab farming was found, focus group discussions suggested that a higher education level might indeed encourage fishers to consider being involved in activities other than capture fishing. The focus group from Kali estuary that was considering mud crab farming if there was financial and educational support, has a higher average education level than the focus group from

Aghanashini estuary. Fishers of FG Aghana did not have any knowledge of farming methods and therefore would not consider such activities and did not show any interest in learning. However, respondents of the survey who were interested in mud crab farming had varied education from only one year in education to higher secondary education showing that formal education level does not always indicate people's understanding of economical sustainability, in this case in the form of small-scale aquaculture activities.

The lack of formal education, however, does not mean a lack of knowledge. The majority of these fishers are from families that have been involved in fishing activities over many generations and therefore possess extensive traditional or local ecological knowledge (Berkes *et al.*, 2010). One of the fisherwomen who had no formal education said she would not need any training as she has been going fishing since she was a child and believes she knows every detail she should. In this way, she also questioned the usefulness of the training programmes. However, it can be argued that climate change and depleting stocks caused largely by overfishing have presented fishers with new challenges they are not familiar with and thus might not have inherent knowledge about these issues. Yet traditional ecological knowledge is not static and also should be perceived as collaborative (Whyte, 2013). The above-mentioned statement yet strongly suggests that any training programme should be delivered in a respectful way and fill possible gaps of knowledge in a sensitive way. Social capital consists of norms and networks (Woolcock, 1998) and is strongly linked to transforming structures such as community groups. It can be seen as both a product of the transforming structures and processes and the cause of them (Department for International Development, 1999). Social capital does not consist only of formal groups but also networks based on shared interests and trust, and similarly to human capital, is not homogenous (Putnam, 2001). The fishers who are involved in formal fishing societies would get financial support in case of emergency or death in the family and receive nets and life vests. Yet, fishers from the Sharavati estuary mentioned that membership in a fishing society does not mean that all of its members would obtain goods, such as gear, equally. Social capital is not always in favour of the people (Putnam, 2001). Besides the benefits of social capital in the form of help from relatives or the extended community, there are also costs related to social capital, especially in the case of strong bonds within certain communities excluding others (Woolcock and Narayan, 2000). The self-group established by the focus group from Kali estuary indirectly proposed that they are more aware of how significant social capital could be an advantage for their livelihoods. This, therefore, leads us back to the idea that human capital proves to be important not only in an economic context, meaning that a higher education level would increase not only the chances of receiving a higher income but also increased social development (Sen, 1997).

Although structures that mediate social capital were ambiguously appraised by fishers, community groups for mud crab farming could be the key structure for mud crab to become a sustainable livelihood resource in Uttara Kannada, as most of the fishers see the lack of land and financial resources as the major obstacles. By establishing community groups similar to the self-group of Kali estuary, fishers would likely enhance their livelihoods, strengthen social capital and increase their competitiveness in the market. Mirera *et al.* (2014) in their study on community organised groups in Kenya found that members of these groups acknowledged that mud crab farming in addition to food supply and direct income also provides employment opportunities and promotes mangrove conservation and restoration. Nevertheless, there were complications with local authorities regarding the use of land and mangroves and also unfair price competition of the crabs due to the lack of policies controlling the market (Mirera *et al.*, 2014). This, therefore, suggests that if small-scale mud crab farming would be promoted and implemented with the help of governmental or non-governmental organisations in southwest India, policies and clear guidelines should be developed regarding land and mangrove use.

### 2.4.2. Natural, physical and financial capital and the transforming structures

Small-scale fisher communities as well as other communities that obtain most of their livelihoods from resource-based activities are highly dependent on natural capital such as biological resources. Yet, natural capital is not static as was seen by fishers recognising a decrease in stocks of fish and crustaceans over their time of fishing. There are no restrictions on the catch size, time and place for fishing in the study sites. Such a phenomenon has also been observed in Chilika lagoon in Odisha state, India by Nayak (2017) where respondents recognised that the high fishing intensity forces fishers to take any size, the perception being that otherwise fish or crustaceans will be caught by somebody else; a risk that cannot be taken in an area with a very low average income.

Another type of natural capital, particularly important for mud crab farming is the land. As previously discussed, the lack of access to land is the main reason reported as to why fishers are not willing or would not be able to undertake mud crab aquaculture. The data of the National Sample Survey Organisation of India shows that in 2003-2004 in Karnataka 40% of households did not own any other land other than their homestead (Rawal, 2008). Land ownership in India is highly complex and while land reforms, to distribute land to the poor and landless, have been implemented over the years, there is still significant inequality, especially regarding scheduled castes and scheduled tribes (Bakshi, 2008). Scheduled castes and scheduled tribes (SC/ST) are the lowest castes and tribes that have been historically marginalised (Besley *et al.*, 2016), yet the Government of India has developed legislation and schemes to empower SC/ST (Ministry of Social Justice and Empowerment, 2017). While fishers are not affiliated to any particular caste due to their occupation, most of the fishers belong to the other backward caste (OBC) which is described as economically and socially vulnerable (Chauhan, 2008). Even though caste affiliation was not identified during the survey, informal conversations and observations suggest that fishers have poor access to land. Mud crab farming could be carried out in mangrove incorporated ponds, yet being a common resource, such a setting might not be the most suitable unless strong community groups with a high level of trust are established.

To be able to obtain an education, receive healthcare and sell their catch, basic infrastructure in the form of transportation, communications, safe shelters, adequate water supply and sanitation and energy are needed, e.g. physical capital (Department for International Development, 1999). According to the Marine Fisheries Census 2010 (CMFRI, 2010), 85 of 86 fishing villages in Uttara Kannada are electrified and 84 have mobile phone coverage, and observations confirmed that there is good basic infrastructure at the study sites. Physical or built capital is a proxy for development in rural areas, as roads, sanitation, water and energy supply attract businesses and tourism (World Bank, 2012; Mikulcak *et al.*, 2015).

While physical capital possessed by fishers in study sites is relatively high, a different picture is revealed for financial capital. It is the most versatile capital but at the same time commonly the least accessible to poor communities (Department for International Development, 1999). While the aim of this study was not to obtain qualitative economic data on income, savings and costs, it was found that the majority of fishers are highly dependent on the income from fishing and do not have any savings or other source of income. On the contrary, when compared to agricultural communities that possess livestock which can be perceived as a store of wealth (Ellis, 2000), fisher communities usually do not possess any such assets. Sen and Homechaudhuri (2017) found that in the Indian Sundarbans mud crab fishers heavily rely on credit known as *dadon*, a system given by middlemen that has a variable interest rate depending on demand. However, no such a custom was found to be present in Uttara Kannada.

One of the critiques of the sustainable livelihood approach is that there are no clear guidelines on how the capital assets should be measured – whether all of the possible assets for each of the capital have to be included in the analysis or only some of them (Morse *et al.*, 2009). Particularly difficult is to assess land ownership as it tends to be very complex and fragmented. Another critique Morse *et al.* (2009) identify is the trust among researchers/development workers and respondents. Fishers interviewed in this study were not willing to disclose the information about their income, therefore it is acknowledged that if respondents withheld information, assets may have been underestimated.

The perception of mud crab by local fishers as profitable indicates that any implementation of sustainable mud crab fishing practices and small-scale farming systems could significantly improve their livelihoods and financial capital. Socio-economic studies in Bangladesh and India under different farming systems (e.g., Ferdoushi and Guo, 2010; Jahan and Islam, 2016; Sen and Homechaudhuri, 2017) have shown that small-scale aquaculture systems have proven to be a lucrative activity which also has the potential to contribute to the wider economic context (Sathiadhas and Najmudeen, 2004).

### 2.4.3. Vulnerability context

Vulnerability is the susceptibility to be harmed (Adger, 2006), and is also strongly linked to the concept of resilience, being the ability to recover from stresses and shocks (Scoones, 1998; Adger, 2006). In the context of the SES framework, vulnerability within the social-ecological system can be caused by external changes in social, economic, and political settings (S) and/or related ecosystems (ECO) that in turn can alter any of the first or second-tier components. The vulnerability context consists of trends and shocks including especially those related to seasonality (e.g., monsoon and weather conditions). Although artisanal fishers are constantly subjected to seasonality, they often have low resilience towards it (Allison and Ellis, 2001). Fishers in Uttara Kannada perceived mud crab collection as an unstable activity because of the high variability in catch from day to day thus suggesting that resource trends are unpredictable.

Fishers could possibly face changes to trends in market prices, although at the moment due to the high demand for mud crab in both the national and international market, prices for mud crabs are stable and only fluctuate slightly according to the price willing to be paid by middlemen. Yet, another important trend that influences fishers is the increasing population in India, and especially the impact of this on coastal areas (Neumann *et al.*, 2015). Respondents have already noticed the effects of this trend in the appearance of increased fishing intensity. Thus, fishers are going to need to adapt to this trend and establish new livelihood strategies. Similar to trends, other stresses are small and regular disturbances, such as occurrences closely related to climate change, for instance, increased water temperature and saltwater intrusion into wells due to sea level rise, which have the potential for long-term impact. Sand mining in the Aghanashini estuary has significantly influenced fishers' livelihoods as it destroys bivalve stocks, while fishers reported that it does not have a direct impact on mud crabs. However, studies have revealed that sand mining negatively affects crustacean and fish populations due to the removal of juveniles (e.g. Sheeba, 2009; Jonah *et al.*, 2015). Although previously sand mining has been considered an extreme, but an irregular event, it is now clear that it should be perceived as regular stress towards which adaptive actions should be established.

Fishers in Uttara Kannada are also influenced by seasonality. There are distinct seasons in southwest India that dictate the life and work of fishers, and cause changes in the availability of fishes and crustaceans. The peak season for mud crabs varies geographically (Kathirvel and Srinivasagam, 1992), but according to a previous study carried out in Karwar, Uttara Kannada district, there are two peaks in the breeding of *Scylla serrata*, one between December–March and another in September–November (Prasad and Neelakantan, 1989). Seasonality itself is predictable and does not impose a threat, however in combination with climate change it could have a negative effect on the inland fisheries sector (Das *et al.*, 2013).

Compared to the previous disturbances, shocks are unpredictable short-term occurrences with immediate impact (Scoones, 1998). Although fishers did not mention any recent shocks that had an impact on their livelihoods, both natural and human health disasters can take place at any time and if communities are structurally vulnerable, with high sensitivity and low resilience, they can suffer (Allison and Ellis, 2001). One of the respondents was a fisherwoman, who had taken over the fishing from her husband as he had serious health problems. As she had been involved in fishing activities since her childhood she could easily adapt to the new situation where she is fully responsible for her household's livelihood. However, for other families, such a shock could have resulted in the household having no income and sliding into poverty.

### 2.4.4. Livelihood strategies and outcomes

Livelihood strategies and outcomes can be seen as the interactions (I) and outcomes (O) of the SES framework. Similarly to the focal action situations, livelihood strategies are influenced by the external conditions and the interaction between them, and they can vary highly between different communities. Even for the same household, livelihood strategies can vary depending on external shocks and stresses (Ellis, 2000). Scoones (1998) identifies three types of livelihood strategies - intensification or extensification (mainly regarding agriculture), diversification and migration. For fishing communities in Uttara Kannada intensification is not possible as the fishing intensity is already arguably too high as fishers report decreases in the mud crab population. While there are no official quantitative data available on changes in the mud crab population in India, the decline has been acknowledged by Rajiv Gandhi Centre for Aquaculture, naming indiscriminate overexploitation (e.g., catching of juveniles, berried female crabs) as the main reasons (Thampi Samraj *et al.*, 2015). Compared to Western Australia, where strong regulations are in place for the commercial and recreational fishery on the minimum size (150 mm carapace width for *S. serrata*) and a prohibition on taking berried females and undersized crabs and limiting the number of pots used (Department of Fisheries, 2018), no such regulations are present in India. However, extensification in the areas fished and species caught could be a strategy for some households that have been focusing on catching only particular species to date.

Allison and Ellis (2001) argue that diversification and high mobility is common among fishing communities especially in low-income countries, however, this was not recorded to be the case in our survey sites in the Uttara Kannada district. Only one respondent has migrated and worked in another state, whereas all other respondents have only lived in the area they grew up in. The majority of fishers were highly dependent on fishing and it would be their only source of livelihood. However, they would not focus on only one type of fishing but would catch various types of fish and crustaceans and women would collect bivalves. Only respondents from agricultural communities would harvest crops. Some of the fishers would work as employees on marine fishing boats. However, the implementation of small-scale mud crab farming systems would be a livelihood diversification that could have a positive effect on fishers' livelihoods. Aquaculture activities also can provide a more stable income compared to capture fishing. Counter to Allison and Ellis (2001) who state that for many artisanal fisher families fishing is 'an opportunistic endeavour', this study found that fishing for these communities is part of their identity. They would not leave fishing for more profitable activities unless absolutely necessary as has also been observed in the state of Odisha, India by Nayak (2017).

### 2.4.5. Institutional context and environmental sustainability

The fishers, mud crabs, estuarine and coastal fisheries and governing organisations and rules are the main subsystems of a complex social-ecological system that, while being relatively independent, interact to produce outcomes (Ostrom, 2007; McGinnis and Ostrom, 2014). Although each of these units is equally important, governance systems (institutional context) can influence the interaction between other subsystems and enhance or hinder development. Institutional context is also important for assessing the capital assets in the context of vulnerability as some of the shocks and trends can be mitigated by the already established institutions and organisations (Morse *et al.*, 2009). Whether referred to as institutional sustainability or institutional context, organisations and institutions play a fundamental role in growth and development (Acemoglu and Robinson, 2008).

In this case study local communities that fish or farm mud crabs can be affected by variables such as government organisations, non-government organisations, middlemen, local village markets, export agencies, hotels, land use rights, operational rules and sanctions. There are several fisheries and aquaculture related government and non-government organisations in India that are active actors in training and promoting certain species, however, based on informal conversations such programmes in Uttara Kannada are not common, yet could take place in the near future. Middlemen, export agencies, hotels and village markets are the units that regulate and reflect the demand for mud crabs. Sen and Homechaudhuri (2017) identified middlemen as ‘conservation agents’ that could be targeted to implement sustainable fishing practices fishers trust them, they possess traditional knowledge and also are aware of the demand and have connections with export agencies or hotels and restaurants. Furthermore, although no evidence of a loan system provided by middlemen in Uttara Kannada was found, such practice could be in place as small-scale fishers have been acknowledged to financially depend on middlemen (Kurien, 1996). Besides, rules and regulations are weak in Uttara Kannada, indicating that it is an area that should be improved. However, any regulations should be introduced carefully taking into account informal cultural institutions and acknowledging that any government interventions can be received with suspicion by small-scale fishers (Jentoft and Chuenpagdee, 2015).

Environmental sustainability can be assessed using various assessment approaches (Little *et al.*, 2016). In regard to fisheries, stock assessment and maximum sustainable yield is considered as the most relevant approaches that can reveal how environmentally sustainable is the fishery of a particular species. While there is no country- or state-level stock assessment of mud crabs at a country-level in the Indo-Pacific region, some regional studies have been carried out showing data on yield and catch per unit effort (CPUE). This could serve as an indirect measure of the abundance of mud crabs. Sen and Homechaudhuri (2017) in their study in Indian Sundarbans found decreased CPUE from March to June and increased CPUE from July up to January of *S. serrata*. A study in the Philippines by Lebata *et al.* (2009) showed that monthly yield could be increased by 46% by releasing hatchery-reared mud crabs and gaining a yield of 5.54 kg ha-1 yr-1. Yet, other studies in the Philippines have shown a yield of 65.4 kg ha-1 yr-1 (Walton *et al.*, 2006) and 4.1 kg ha-1 yr-1 (Lebata *et al.*, 2007) and a similar trend of CPUE increasing in certain periods but not the same months as in India due to possible difference in the breeding season. Although this data set is limited, as no rapid decline has been seen in CPUE, it could suggest that mud crab fishing can be seen as environmentally sustainable. Yet, further research and monitoring are necessary as fishers are experiencing a decrease in mud crab populations. Furthermore, the stock enhancement would be beneficial and, taking into account the increasing human population and thus consequent demand, small-scale aquaculture should be considered as an alternative providing a steady source of income, while maintaining wild populations.

## 2.5. Conclusions

Each social-ecological system is a complex, multi-tier system in which some components at a particular time and place are more important than others. The sustainable livelihood approach is a useful analytical tool to identify such variables that can later be analysed through the SES framework. The mud crab is perceived as a good source of income among fisher communities in Uttara Kannada, yet at present, it is not recognised as a steady source of income due to the unpredictable fishery catches, thus is not an economically sustainable resource in the current mode of practice. Fishers are constantly subjected to various external stresses and trends such as seasonality and decreasing fish and crustacean stocks. However, due to the lack of significant information on catch effort, yield and recruitment, it is complicated to predict the livelihood outcomes in the long term. Besides, while respondents were aware of mud crab farming, the majority stated the lack of land and financial resources as the main barriers to consider this as income generating activity. This indicates that governance systems, in particular, the property-rights systems play an important role in ensuring equal access to land and livelihood diversification. Only a small minority expressed any interest in undertaking such activity. However, it could be seen as a new type of interaction, leading to beneficial outcomes. Compared to the body of literature stating that fishers adopt diversified livelihood strategies, it was found that respondents in Uttara Kannada fully rely on fishing and fishing related activities.

The sustainable livelihood approach allowed exploring how livelihood outcomes could be influenced by adopting different livelihood strategies and how that would consequently affect the livelihood assets. Owing to this and its holistic view, the approach has been mainly used as a practical tool for poverty reduction programmes. However, to be able to identify all the elements, in particular, the livelihood assets, active participation or already existing data sets are necessary.

# Chapter three: Socio-economic drivers and limitations to mud crab farming as a sustainable small- and medium-scale enterprise

## 3.1. Introduction

As a response to the increasing global human population and higher fishing intensity leading to the depletion of fish stocks (FAO, 2011; Allan *et al.*, 2005), the aquaculture sector has seen rapid growth in the last few decades and is the fastest growing food production sector in the world (FAO, 2016). Aquaculture, the farming of fish, crustaceans, molluscs or aquatic plants with external input and ownership of the stock cultivated (FAO, 1988), not only has a direct impact on food security and poverty alleviation of rural poor but also enables local communities economically by undertaking fish farming or being employed on fish farms (Toufique and Belton, 2014). Aquaculture also has the potential to contribute significantly to overall economic growth. However, aquaculture can compete with capture fisheries by negatively affecting natural habitats and limiting access to those who are heavily dependent on capture fisheries and do not have the means for fish farming. Shrimp farming that bloomed in the 1980s is an example of how aquaculture can have a destructive impact. The development and widespread adoption of commercial shrimp hatchery technologies meant a rapid increase in shrimp farming leading to the development of large-scale farms in, for instance, India, Indonesia, Bangladesh, Thailand, Ecuador, Taiwan and others (Kumar and Engle, 2016). Coastal areas were negatively impacted as mangroves in many cases were cleared for pond and canal construction, and efflux of untreated pond water into receiving estuaries or coastal waters resulted in pollution (Primavera, 2006; Ashton, 2008). Besides the negative environmental impact, social issues regarding the exclusion of local communities, especially those involved in fishing, were also seen (Béné, 2015; Blythe *et al.*, 2015). These issues emerged as shrimp farming was not appropriately regulated and executed in a sustainable manner. However, more recently the shrimp farming sector and international organisations have been working towards transforming shrimp farming and the aquaculture sector as a whole into one that is more sustainable (Bostock, 2011; Eigaard *et al.*, 2014; Fujii *et al.*, 2017).

As mentioned above, a widely accepted narrative is that fish is vital for food security for rural poor communities and is rather a form of livelihood diversification or a subsistence activity and can contribute to poverty alleviation. However, the counterargument is that the fish farmed by these communities are consumed by the middle class instead and often exported to the Global North (Beveridge *et al.*, 2013; Golden, 2016), therefore not solving local food security and/or poverty challenges. Amid these two narratives, a counter-narrative of aquaculture as a small- and medium-scale enterprise (SME) has emerged highlighting the indirect effects of aquaculture on poverty alleviation. Developing aquaculture as SME can create growth linkages – employment opportunities, demand for feed and other inputs (Filipski and Belton, 2018).

Owing to the high economic value of *S. serrata* and the prospect of environmentally sustainable farming set-ups, this study focuses on another resource system of the complex social-ecological system involving mud crabs as the main resource units. This study aims to assess the feasibility of mud crab aquaculture as a sustainable small and medium size enterprise and identify socio-economic drivers and limitations as perceived by mud crab farmers already involved in this activity in coastal Andhra Pradesh. Thus, the findings regarding crab farming experience and practices in Andhra Pradesh can be used as examples of successful and sustainable implementation of small-scale mud crab farming in Karnataka.

## 3.2. Materials and methods

### 3.2.1. Study area and data collection

The fieldwork for the assessment of socioeconomic feasibility of mud crab farming was undertaken during September and October 2019 in Andhra Pradesh, which is the leading state of aquaculture in India contributing 40% of the total farmed fish export value of India (Subramanyam and Prasad, 2017). The main aquaculture species are prawns, catfish and carp, and mud crab farming has also been expanding in recent years.

The socioeconomic data on small-scale mud crab farming was collected by using a pre-tested structured questionnaire through direct face-to-face interviews. The interviews were conducted in the local language Telugu with the aid of a translator. The questionnaire was divided into five sections – farm management practices of mud crabs, access to market and extension services (such as agencies providing information and training), costs and returns of production, the environment and demographics (Appendix 1). A snowball sampling approach (research participants help identify other potential participants) was used after the first respondents were identified by local authorities and researchers. In total 37 respondents were interviewed in nine locations across a 500 km transect. (Fig.3.1).

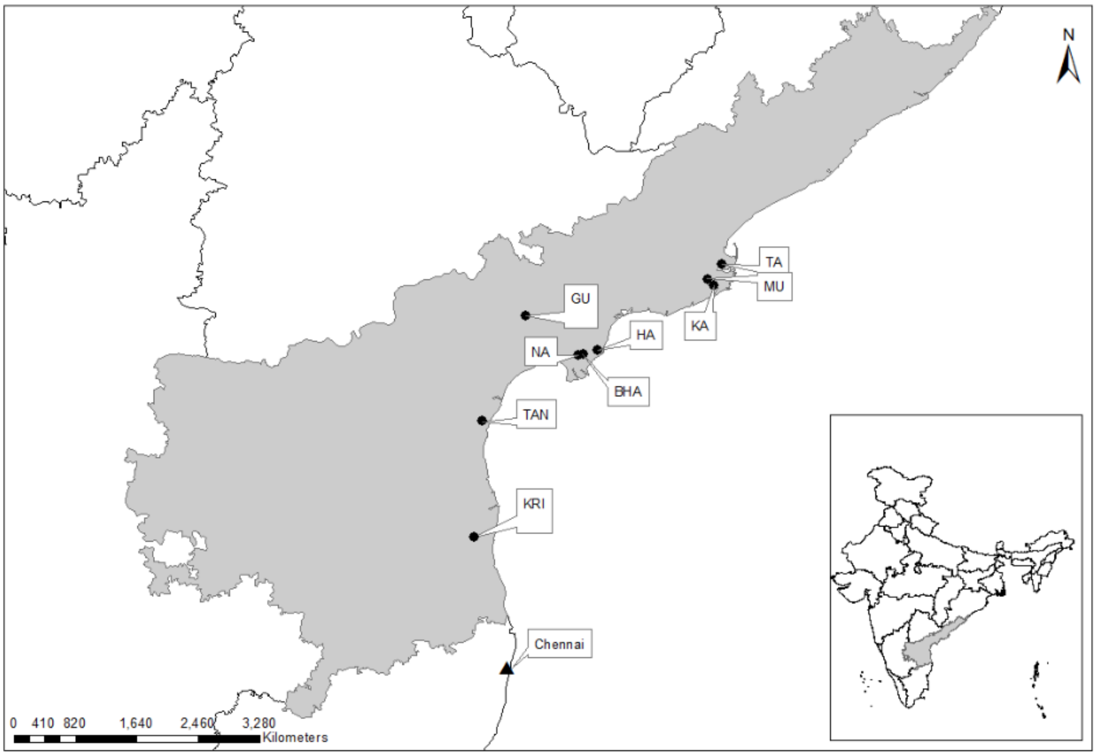


*Figure 3.1. Study sites across Andhra Pradesh – Krishnapatnam (KRI) (n=7), Tangaturu (TAN) (n=1), Guntur (GU) (n=1), Nagaylanka (NA) (n=5), Bhavadevarapalle (BHA) (n=5), Hamsaladeevi (HA) (n=1), Tallarevu (TA) (n=7), Mummidivaram (MU) (n=7) and Katrenikona (KA) (n=3).*

### 3.2.2. Data analysis

The processed data were divided into two groups according to the size of the farm – small-scale (less than 2 ha) and large-scale (more than 2.01 ha) (FAO, 2017). The data were analysed using the Statistical Package for Social Scientists (IBM SPSS Statistics 24). The Chi-Square test of independence was used to determine whether there was a significant relationship between the two variables. The graphic analysis was performed in SPSS v.24 and R Studio.

Average itemised fixed and variable costs per culture were indicated and cost per unit was calculated where possible. As not every respondent disclosed all fixed and variable costs, the average total costs and the average cost per unit are not necessarily reported by the same respondents and thus may vary. Economic analysis was performed by calculating total costs (TC), total revenue (TR), net revenue (NR), benefit-cost ratio (BCR), profitability ratio (PR) and return on an investment expressed as a percentage (ROI%). Six respondents were yet to harvest their mud crabs at the time of the survey, and thus were unable to provide information on revenue, and were excluded from further analysis on profit. Total costs (TC) consist of total fixed costs (TFC) and total variable costs (TVC). TFC included land lease, preparation of the pond, fencing and maintenance that comprised watch and ward costs (security services that were provided by an individual or a family residing on the site). TVC included costs for crab seed, feed, transportation, labour, water and electricity. Total revenue (TR) was obtained by knowing the amount of production and the selling price at the time. Net revenue (NR) was determined by deducting total costs from the total revenue. The benefit-cost ratio (BRC) was obtained by dividing total revenue by the total cost of production. Return on investment (ROI) expressed as a percentage was obtained by dividing net revenue by the total cost of production and multiplied by 100.

TC=TFC+TVC

TR=selling price x production

NR=TR – TC

BRC=TR / TC

ROI (%) = NR / TC x 100

To assess the feasibility of mud crab farming as a small- and medium-scale enterprise, it is important to consider how the costs and benefits change over time. To do this, discounted benefit-cost analysis was conducted. ‘Discounting the future’ is a common approach, where a discount rate or cost of capital is applied to present costs and befits to assess the net present value (NPV) at the end of the project. The discount rate depends on the type of investment and business. Corporate businesses often base their discount rates on a weighted average cost of capital (WACC) with added accounting for additional risks, thus reaching 15% on average (Jagannathan *et al.*, 2016). On the other hand, governments apply a social discount rate (SDR) that is significantly lower as government funded projects benefit wider society over a longer period of time. Although there is no universal SDR, the rates between 3.5% (Moore *et al.*, 2004; Freeman *et al.*, 2018) and 4.5% (Quinet *et al.*, 2013) have been recommended. The discount rates used in studies assessing the economic feasibility of aquaculture range from 10% in copepod culture in Denmark (Abate *et al.*, 2015), and Indian large-scale carp farming in India (Bag *et al.*, 2014), to 15% in small-scale fish farming in Zambia (Namonje-Kapembwa and Samboko, 2020) and Ghana (Anokyewaa and Asiedu, 2019). Thus to account for variable market conditions, three discount rates were applied – low 5%, medium 10% and a higher discount rate of 15%. The discounted NPV was calculated using the following formula, where r = discount rate, t = time in years:

$$NPV = \sum_{t=0}^{T} (Benefits_t - Costs_t) \left(\frac{1}{1+r}\right)^{t}$$

Respondent data on costs and, in particular, profit only depicted one year, therefore five different scenarios (Table 3.1) were used to predict net present value over 5, 10, and 15 years with different harvest successes. Such time frames were chosen as fishers and aquaculture practitioners respond to changes and might switch to species with higher market price or species that are easier to maintain. Mean total fixed and variable costs and profit was calculated based on the mean values given by the respondents except two lowest and two highest due to high variability. Crablets were restocked every year as they were fully harvested at the end of the season. The maximum harvest is set to be 45% (Moksnes *et al.*, 2015b; Islam *et al.*, 2018; Mwaluma and Kaunda-Arara, 2021), the mean harvest is set to be 23% based on the average survival rate seen in this study and also based on findings by Mirera and Moksnes (2014). The survival rate for the low scenario is 10% (Mirera and Moksnes, 2014).

For all the scenarios it was assumed that:

1. Each crab weighs 500 g (1st quality class (big). Based on personal correspondence it can be assumed that most of the harvested crabs will fall under this category and only about 10-20% might be in the 1st class (XL) or 2nd class category.
2. The selling price is £10.13/kg (975 Rs/kg), which is the average price reported by respondents in October 2019.
3. Small-scale farmers on average stocked 1,978 crablets at the beginning of the season, while the average number for large-scale farmers was 4,875 crablets.
4. Mud crab farmers have one crop per year and the growth period is 5 to 6 months.

Sensitivity analysis was carried out to account for changes in input variables such as selling price and size of the crab. To estimate the effects of these changes four assumptions were applied - 1. Highest reported selling price (£12.46/kg or 1,200 Rs/kg), 2. Lowest reported selling price (£6.23/kg or 600 Rs/kg), 3. Crabs at harvest weigh 700 g each, 4. Crabs at harvest weigh 300 g. Each of these assumptions was exclusive and did not include other assumptions at the same time and were applied for all the scenarios with a 10% discount rate for 10 years. Calculations of the NPV and sensitivity analysis were conducted in Microsoft Excel.

*Table 3.1. Scenarios for discounted benefit-cost analysis. Survival rates differ significantly depending on husbandry practices, quality of stock, stocking density and growth period, yet common rates vary between 10 and in some cases 60% (Mann et al., 2007; Mirera and Moksnes, 2014; Moksnes et al., 2015b; Islam et al., 2018; Mwaluma and Kaunda – Arara, 2021).*

| **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 |

It is important to note that this study has several limitations. Firstly, not every respondent was able or willing to report precise itemised expenses. As “outsiders”, the research team was met with suspicion and often became the object of observation themselves, which is not uncommon in rural (ethnographic) research (Ranjan, 2011). Secondly, with limited reference data on the benefits and costs of mud crab farming, it is difficult to validate the findings. Therefore, it was important to remove the outliers before calculating the average values of the total benefits and total costs for the discounted benefit-cost analysis.

## 3.3. Results

### 3.3.1. Demographics and characteristics of mud crab farms

All respondents interviewed were male, aged from 26 to 81 years with Telugu as their native language. The resource systems varied in size from 0.405 ha to 16 ha, yet the majority of respondents (64.9%) had small-scale mud crab farms, ranging in the size from 0.405 ha (1 acre) to 2 ha (see Table 3.2). The two largest of the large-scale farms covered 16 and 12 ha farms, while the majority of the farms were between 2.01 and 4.9 ha in size. The majority of large-scale farmers (53.8%) owned the land the farms were located on or leased additional land, while small-scale farmers tend to lease the land or used common resources. All respondents from Krishnapatnam (KRI) were undertaking crab farming in a natural water body – a large lake-like water basin that has been created after building a thermal power station in the area. It receives water from nearby canals and fills up with rainwater. The local community has divided it into one acre ponds (equal to 0.406 ha) and there are about 20 people undertaking crab farming. The majority of respondents had one or three ponds, yet one respondent had obtained five ponds (5 acres or 2.03 ha), which placed him into the large-scale farming group. Respondents from KRI did not pay any lease but paid for a family to stay on the site serving as security guards. Furthermore, five respondents, who used to be fishers, from Tallarevu (TA) and Mummidivaram (MU) had acquired 1 ha in the mid-1980s from the District Rural Development Agency (DRDA) after being trained in aquaculture. However, one respondent was using cage culture for the first time, where crabs were kept in individual boxes partially submerged in the water. Most of the crab farmers were aware of the cannibalistic behaviour of the crabs and provided some shelter (old tyres, pipe fragments, palm tree branches) (personal observation, EA).

All of the respondents were mainly involved in ‘grow out’ aquaculture which means acquiring and farming early juvenile stage crabs to reach their adult stage in the aquaculture system. At the moment of the study, there was only one commercial mud crab hatchery providing crab farms across all of India which produce around one million crab seeds per year (personal correspondence, EA). They offer crab instars that are approximately 0.5 cm in size (carapace width) and also crablets that are instars grown up to reach about 2-4 cm in size. Thus, farmers can choose as the price depends on the size. Commonly respondents stocked around 800 to 1,200 instars and 400 to 500 crablets per acre (see Appendix 2 for individual data). In contrast, fattening is done with slightly larger crabs which can already be sub-adult or adult crabs. Due to high competition to obtain the seeds, the majority of the respondents not only buy commercially produced crab instars, but also rely on wild stock collected by local fishers or procured from crab dealers in Chennai. Thus, when asked to assess how easy or difficult it is to access crab seeds, the majority answered that it is very difficult (51.4%) or somewhat difficult (27%) (Fig.3.2). The crabs were kept in the ponds for 3 to 8 months, with 5.3 months to be the average duration. The survival rate varied significantly from as low as 2% to as high as 60%, but the average survival rate was merely 23% (including mass mortalities).

Respondents did not face any issues with water availability as farms were located near rivers, man-made canals or seaside. Respondents from KRI did not maintain water quality in any way, including the respondent included in the large-scale group, while the rest of the large-scale farmers (69.2%) either regularly checked water salinity, temperature, pH and bacterial load or treated water chemically (Table 3.2). The chemicals used were fertiliser dolomite lime to balance pH, fertiliser diammonium phosphate (DAP), urea and superphosphate that are common in more intensive aquaculture setups such as shrimp aquaculture. The Chi-Square test of independence indicated that there is a statistically significant difference between the type of water quality maintenance and the main source of income (p=0.019). Chemicals are used mainly by those involved both in shrimp and crab farming.

Access to feed was assessed as easy by 54.1% of a total of 37 respondents, yet while none of the large-scale farmers evaluated it as very difficult, and only 8.3% evaluated it as somewhat difficult, 47.4% and 5.3% of small-scale farmers identified the access to feed as somewhat difficult and very difficult, respectively. Thus, a correlation between the perception of access to feed and the scale of crab farms was found (p=0.042). The majority of small-scale crab farmers (58.3%) used chopped fresh fish as feed, while the majority of large-scale farmers (69.2%) used dried fish, yet there was a correlation between the scale and the type of feed. The amount of feed given greatly varied between farms, but on average small-scale farmers used 1608 kg of live fish per culture (5-6 months) and large-scale farmers used 7600 kg/culture. Both small- and large-scale farmers practised increasing the amount of feed by 2-3 kg each month to reach the total indicated above. Similarly, they would also assess if more or less feed was required by keeping track of any excess feed in the pond. Feed was mainly procured from local fishers or landing sites. For the majority of respondents (43.2 %), mud crab farming was their primary source of income, followed by crab and shrimp farming (alternating between crabs and shrimps). Small-scale mud crab farmers had a more diversified source of income compared to large-scale farmers (Fig. 3.3).

*Table 3.2. Summary of the key attributes of mud crab farmers.*

| Variables | Small-scale (n=24) | | Large-scale (n=13) | |
|---|---|---|---|---|
| **Education** | Frequency | Percentage (%) | Frequency | Percentage (%) |
| - No formal education | 5 | 20.8 | 2 | 15.4 |
| - Primary school | 5 | 20.8 | 3 | 23.1 |
| - Middle school | 2 | 8.3 | 1 | 7.7 |
| - Secondary school | 4 | 16.7 | 7 | 53.8 |
| - University degree | 7 | 29.2 | - | - |
| **Type of farming** | | | | |
| - Grow out | 14 | 58.3 | 12 | 92.3 |
| - Fattening | 6 | 25 | 1 | 7.7 |
| - Both grow out and fattening | 4 | 16.7 | - | - |
| **Source of crabs** | | | | |
| - Commercial hatchery | 6 | 25 | 6 | 46.2 |
| - Wild stocks | 15 | 62.5 | 1 | 7.7 |
| - Both commercial and wild stocks | 2 | 8.3 | 6 | 46.2 |
| **Land** | | | | |
| - Owned | 9 | 37.5 | 7 | 53.8 |
| - Leased | 6 | 25 | 1 | 7.7 |
| - Common land | 7 | 29.2 | 1 | 7.7 |
| - Owned and leased | 8.3 | 8.3 | 4 | 30.8 |
| **Size** | | | | |
| - <0.5 ha | 3 | 12.5 | NA | NA |
| - 0.6-1.0 ha | 10 | 41.7 | NA | NA |
| - 1.01-2.0 ha | 11 | 45.8 | NA | NA |
| - 2.01-2.5 ha | NA | NA | 5 | 38.5 |
| - 2.6-4.9 ha | NA | NA | 5 | 38.5 |
| - >5 ha | NA | NA | 3 | 23.1 |
| **Maintenance of water quality** | | | | |
| - Not maintained in any way | 6 | 25 | 1 | 7.7 |
| - Checking salinity/pH/bacterial load | 1 | 4.2 | 5 | 38.5 |
| - Water exchange/pumping | 11 | 45.8 | 1 | 7.7 |
| - Chemical treatment | 3 | 12.5 | 4 | 30.8 |

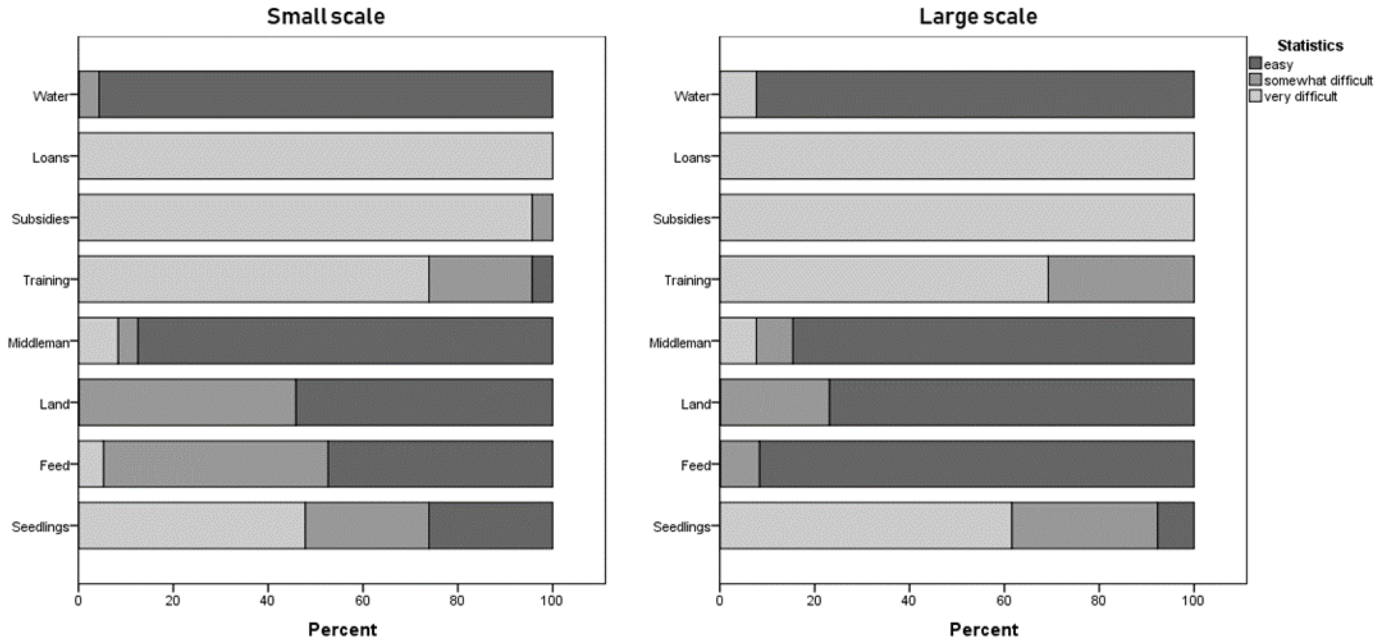


*Figure 3.2. Perception (%) of mud crab farmers of access to essential items for mud crab farming.*

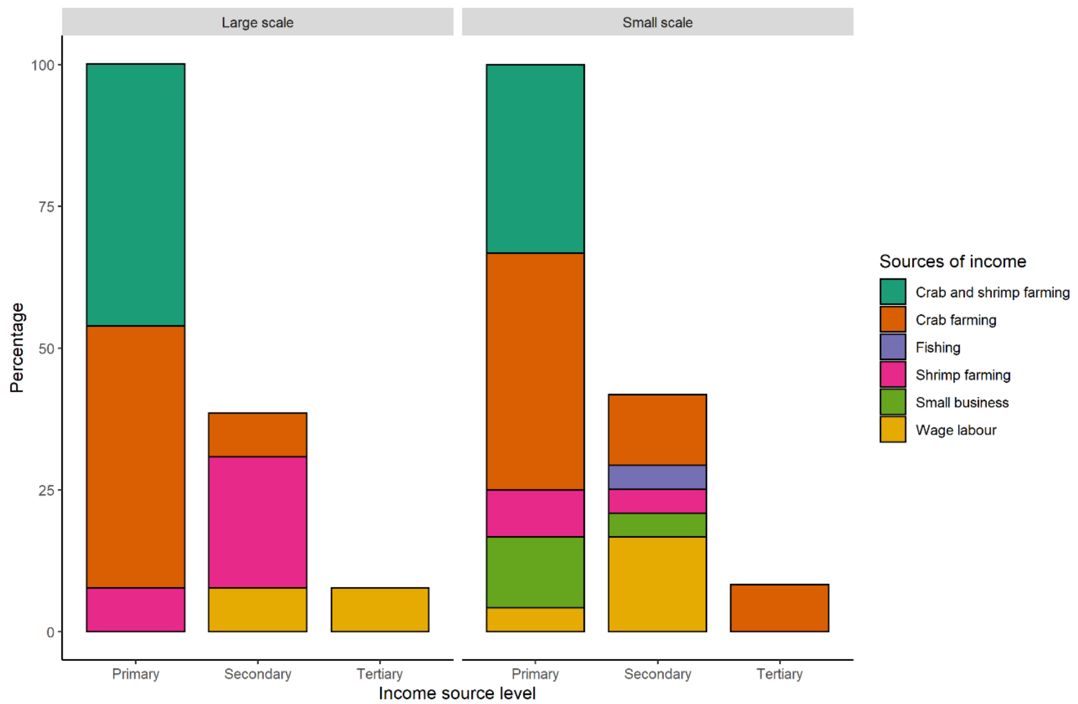


*Figure 3.3. Primary, secondary and tertiary sources of income of small- and large-scale mud crab farmers (%).*

### 3.3.2. Perceptions of the market, access to support and environmental issues

Subsequently, respondents were asked about the access to the market, information and assistance, in other words, the influence of social, economic and political settings. As expected for this species, the majority (83.8%) sold the crabs to a middleman that further sold them mainly for export to Singapore for instance, and all except one respondent were aware of it. Hardly any (two respondents or 5.4%) were not satisfied at all with the service of their middleman, while the majority (70.3%) were somewhat satisfied. The main reason for not being 'very satisfied' was the uncertainty of whether the prices set by the middlemen are fair. The price depends on the size and the quality of the crab, and it fluctuates depending on the international demand and season (Table 3.3). The most common way to deliver harvested crabs was by transport organised by a middleman. All of the large-scale farmers used this option, while small-scale farmers also used their own transport (4.2%) or used public transport (12.5%).

*Table 3.3. Quality classes and the average price reported by crab farmers in October 2019. The Indian rupee is equivalent to 0.01039 GBP (10.06.2020)*

| Quality class | 1st class (XL) | 1st class (big) | 2nd class | 3rd class |
|---|---|---|---|---|
| **Description** | >800g, intact | 500 – 800g, intact | 300-500g, intact | 300-800g, with physical damage |
| **Average price (Indian Rupees)** | £15.48 /kg (£11.42 to £17.63) | £10.13 /kg (£6.23 to £12.46) | £5.79 /kg (£2.59 to £7.27) | £3.12/kg (£2.59 to £5.19) |

While skills and knowledge on fishing practices are passed down through generations, aquaculture practices can be more intricate and require some specialist knowledge. The most common source of information on how to farm crabs and what is necessary was from people from the neighbouring district (54.1%), followed by a local person that had been already involved in crab farming or a crab distributor (16.2% and 10.8%, respectively), trial and error approach (10.8%), and the internet (8.1%). Only five respondents were part of an aquaculture society that supports its members with equipment and information. The National Centre for Sustainable Aquaculture (NaCSA) is an outreach organisation established and funded by the Marine Products Exports Development Authority (MPEDA) in India and has several small branch societies across Andhra Pradesh. For instance, there are five such societies in Tallarevu. NacSA aims to promote sustainable aquaculture practices in particular among small and marginal farmers. However, access to training in aquaculture practices was assessed as very difficult by the majority of the respondents along with almost impossible access to loans and subsidies (Fig 3.2). More than half of mud crab farmers (75.7%) thus disagreed with the statement that they receive enough support from various organisations, yet 97.3% said that they would be willing to expand if they received support (Fig.3.4). Although mud crab farming is not perceived as an unambiguously stable or profitable activity, all of the respondents agreed that they would encourage their friends and family to undertake mud crab farming. Thus, this could indicate that on the whole, the perceived benefits outweigh the risk and for livelihood diversification purposes, mud crab farming is indeed seen as a valuable income generating activity.

Fishers have been reporting a decrease in the wild mud crab population; thus mud crab farmers were asked whether they have noticed any changes. The majority (48.6%) responded their impression is that the wild mud crab population has slightly decreased, and 29.7% reported it to be significantly decreasing. The biggest environmental issues were reported to be increased water temperature and water pollution and saltwater intrusion (Table 3.4). Consequently, these were mentioned as the reasons for disease and mortality of crabs as 78.4% of respondents had noticed sick or temperature affected crabs in their ponds. Mangrove destruction harming their crab culture was only reported by small-scale crab farmers.

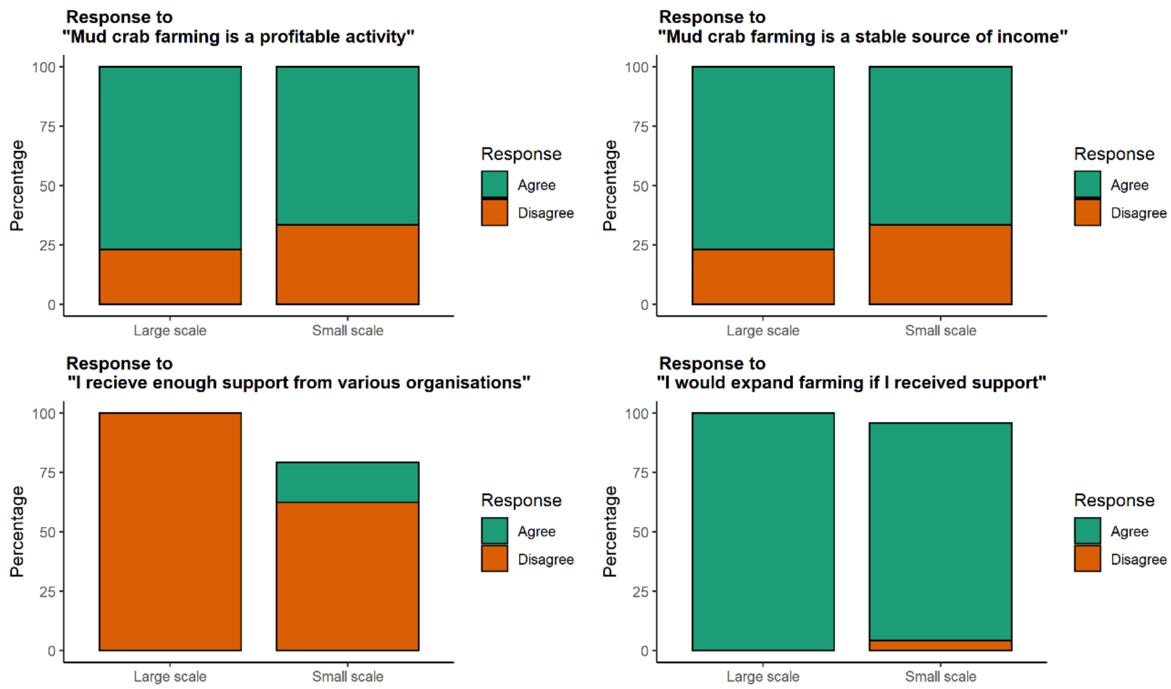


*Figure 3.4. Perception of statements (%) of mud crab farmers regarding profitability and stability of mud crab farming and support from various organisations.*

*Table 3.4. Perception of mud crab farmers of environmental trends and shocks (%).*

| PARAMETER | MINIMAL | | MODERATE | | SIGNIFICANT | |
|---|---|---|---|---|---|---|
| | Small-scale | Large-scale | Small-scale | Large-scale | Small-scale | Large-scale |
| Flood | - | - | - | - | 25 | 15.4 |
| Freshwater influx | - | 7.7 | 12.5 | - | 16.7 | 23.1 |
| Saltwater intrusion | 16.7 | 7.7 | 8.3 | 23.1 | 25 | 30.8 |
| Mangrove destruction | | - | 4.2 | - | 20.8 | - |
| Increased water temperature and pollution | 16.7 | - | 8.3 | 15.4 | 37.5 | 38.5 |

### 3.3.3. Investment costs and benefit-cost analysis

Small-scale farmers invested the most in fencing, feed and crablets sold in kilograms, while large-scale farmers spent the most on crab instars and crablets sold per piece and digging and preparing ponds (Table 3.5). Besides, one of the biggest differences was the number of people involved in harvesting and thus consequently the cost of this capital, that was on average ~£139 (13,452 Indian rupees) per culture for a small-scale farm and ~£272 (26,192 Indian rupees) per culture for a large-scale farmer. The total cost of production was more than two times higher for large-scale farmers compared to small-scale farmers. There was a difference in the total costs as a sum of all itemised costs obtained from the respondents there were able to report this information and between the total un-itemised costs obtained from all respondents.

Based on the individual fixed and variable costs, the average cost per one unit of fixed and variable capital such as land and feed was calculated (Table

3.6). As not all detailed costs were reported by the same respondents, the price per unit multiplied by the quantity does not necessarily equal the average total costs. Yet, from the price per unit it is possible to see that most of the itemised costs are lower for large-scale farmers compared to small-scale mud crab farmers, except for costs for fences and crablets sold in kilograms.

*Table 3.5. Average itemised fixed and variable costs per culture for small-scale and large-scale mud crab farmers.*

| | **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** |

Note: Values are expressed as average ± standard deviation (SD)

a Indian rupee is equivalent to 0.01039 GBP (10.06.2020)

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

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

d Total cost = Capital costs + Operational costs

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

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

*Table 3.6. Average itemised fixed and variable costs per unit for small-scale and large-scale mud crab farmers.*

| | Item | Unit | Cost per one unit (£)[a] | |
|---|---|---|---|---|
| | | | **Small-scale** | **Large-scale** |
| **Fixed costs** | | | | |
| | Land lease (n=7, n=5)[b] | ha/year | 325±103 | 292±56 |
| | Digging and preparing the pond (n=9, n=5) | ha | 146±67 | 119±34 |
| | Fencing (n=5, n=9) | ha | 221±154 | 367±456 |
| **Variable costs** | | | | |
| | Crab instar (0.5cm) (n=12, n=7) | piece | 0.12±0.02 | 0.08±0.01 |
| | Crablet (2-4cm) or crabs for fattening (n=0, n=5) | piece | n/a | 0.18 |
| | Crablet (2-4cm) or crabs for fattening (n=13, n=4) | kg | 5.4±1.53 | 5.7±0.59 |
| | Feed (n=5, n=9) | kg/culture | 0.30±0.11 | 0.24±0.16 |
| | Transportation (n=16) | culture | 209±49.3 | 174±48.6 |
| | Labour (n=13, n=10) | person/day | 6.9±2.41 | 5.3±0.32 |
| | Water/electricity (n=8, n=6) | culture | 295±36.4 | 117±31.6 |
| | Maintenance [c] (n=12, n=8) | culture | 195±178 | 1479±985 |

Note: Values are expressed as average ± standard deviation (SD)

a Indian rupee is equivalent to 0.01039 GBP (10.06.2020)

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

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

Nonetheless, bigger investment also can mean bigger losses in case of disease outbreaks. Four small-scale farmers and two large-scale farmers lost all of their crabs due to increased water temperature or white spot virus outbreaks, resulting in a significant loss. Yet even the farmers who did not lose all of their harvest faced a significant decrease in numbers due to the same above mentioned reasons. To assess profitability, total revenue (TR), net revenue (NR), benefit-cost ratio (BCR) and return on investment (ROI) were calculated (Table 3.7). The economic indicators varied significantly between mud crab farmers, yet the average net revenue was only positive for the small-scale farms. However, it should be noted that it was largely because of the farms with ROI of 622 and 998%, which should be taken cautiously as these farmers did not report itemised costs or detailed information on the crab weight they sold. This shows how average values not always can be indicative of the feasibility as, while the average value is positive, more than a half (n=13) of the small-scale farmers included in this analysis had low a BCR indicator (value above 1 indicates profit) and a negative ROI%. Only two large-scale farms had positive ROI% and beneficial BCR. Overall, it can be concluded that this harvest brought losses to the majority of the mud crab farmers despite the scale.

*Table 3.7. Individual profitability indicators– total revenue (TR), net revenue (NR), benefit-cost ratio (BCR) and return on investment (ROI%) for all small and large-scale mud crab farms (excluding six crab farmers, who had not harvested at the time of interviews and one small scale mud crab farmer that had not provided information on total profit). The Indian rupee is equivalent to 0.01039 GBP (10.06.2020).*

| **Small-scale (n=20)** | | | | **Large-scale (n=10)** | | | |
|---|---|---|---|---|---|---|---|
| TR (£) | NR | BCR | ROI% | TR (£) | NR | BCR | ROI% |
| 909 | -1429 | 0.389 | -61 | 3637 | -1559 | 0.700 | -30 |
| 0 | -3324 | 0 | -100 | 5610 | -15432 | 0.266 | -73 |
| 327 | -1751 | 0.158 | -84 | 1559 | -364 | 0.811 | -19 |
| 1455 | -810 | 0.642 | -36 | **2598** | **1397** | **2.165** | **116** |
| 468 | -425 | 0.524 | -48 | 1559 | -7550 | 0.171 | -83 |
| 2057 | -2629 | 0.439 | -56 | 1299 | -3398 | 0.277 | -72 |
| 0 | -2187 | 0 | -100 | 0 | -6368 | 0 | -100 |
| **2286** | **327** | **1.167** | **17** | 312 | -13351 | 0.023 | -98 |
| 1766 | -1901 | 0.482 | -52 | 0 | -446 | 0 | -100 |
| 1766 | -499 | 0.780 | -22 | **17922** | **12223** | **3.144** | **214** |
| 1766 | -499 | 0.780 | -22 | | | | |
| **4738** | **3069** | **2.839** | **184** | | | | |
| **4738** | **3304** | **3.304** | **230** | | | | |
| **4738** | **3069** | **2.839** | **184** | | | | |
| **17922** | **16290** | **10.983** | **998** | | | | |
| **21507** | **18530** | **7.225** | **622** | | | | |
| 0 | -4000 | 0 | -100 | | | | |
| 1039 | -758 | 0.578 | -42 | | | | |
| **2857** | **754** | **1.359** | **36** | | | | |
| 312 | -2390 | 0.115 | -88 | | | | |

### 3.3.4. Feasibility assessment of mud crab farming

Benefit-cost analysis of one isolated year gives a static picture of a business that is influenced by many various factors affecting the success of the harvest. Therefore discounted benefit-cost analysis was carried out based on the mean costs (excluding two higher and two lower mean values) and mean profit in five different scenarios, with three different discount rates and over three different time periods. The average total fixed costs excluding the outliers were calculated to be £465 (44,772 Indian Rupees) for small-scale farmers and £1954 (188,143 Indian Rupees) for large-scale farmers. Average total variable costs were significantly higher – £1602 (154,236 Indian Rupees) and £3905 (375,933 Indian Rupees) for small and large-scale farmers, respectively. Results show that if the crab survival rate each year is 23% (medium scenario, average survival rate recorded by the respondents), both small- and large-scale mud crab farmers gain some profit in long term (Table 3.8.). The two most profitable scenarios are the high and the high/low scenario, the latter indicating that for long term profit, the effects of mass mortalities can be reduced by obtaining higher survival rates in the following year. The low scenario unsurprisingly showed that all farmers would suffer significant losses, yet while the medium/low scenario would bring losses to large-scale mud crab farmers, small-scale farmers would still obtain a positive net present value (NPV), albeit low.

Sensitivity analysis was performed to assess the effect of changes in variables, such as the price and size of the crab on the feasibility of mud crab farming in 10 years with an expected discount rate of 10% (Fig.3.5). Net present value in the case of the high scenario would increase by 37% for both small and large-scale farmers if the price was to increase to £12.46/kg and by 64% for both small and large-scale farmers, if the crab size was 700g. At the same time if the price decreased to £6.23/kg and the size of each harvested crab was 300g, both small- and large-scale mud crab farms would experience a decrease in profit in high and high/low scenarios, but only large-scale farmers in the high/low scenario would experience losses. The highest losses and gains are seen in the medium/low scenario and in the case of the low scenario, BCR is negative for both small- and large-scale mud crab farms even if the price and size increase as the survival rate is a dominant factor.

*Table 3.8. Net present value (NPV) for small- and large-scale farms in five different scenarios with three different discount rates.*

| | | Small-scale farms | | | Large-scale farms | | |
|---|---|---|---|---|---|---|---|
| | | **5 years** | **10 years** | **15 years** | **5 years** | **10 years** | **15 years** |
| Scenario | Discount rate | NPV (£)* | NPV (£) | NPV (£) | NPV (£) | NPV (£) | NPV (£) |
| **High scenario** | Zero discount rate | 14,062 | 28,588 | 43,115 | 34,072 | 70,099 | 106,126 |
| | 5% discount rate | 12,113 | 21,969 | 29,691 | 29,241 | 53,683 | 72,835 |
| | 10% discount rate | 10,548 | 17,387 | 21,633 | 25,359 | 42,319 | 52,850 |
| | 15% discount rate | 9,274 | 14,116 | 16,523 | 22,199 | 34,207 | 40,178 |
| **High/low variable scenario** | Zero discount rate | 7,049 | 11,058 | 18,572 | 16,788 | 26,888 | 45,631 |
| | 5% discount rate | 6,049 | 8,762 | 12,761 | 14,292 | 21,131 | 31,105 |
| | 10% discount rate | 5,256 | 7,128 | 9,334 | 12,314 | 17,032 | 22,534 |
| | 15% discount rate | 4,618 | 5,932 | 7,188 | 10,723 | 14,034 | 17,168 |
| **Medium scenario** | Zero discount rate | 3,042 | 6,549 | 10,057 | 6,911 | 15,777 | 24,643 |
| | 5% discount rate | 2,572 | 4,951 | 6,816 | 5,722 | 11,737 | 16,450 |
| | 10% discount rate | 2,194 | 3,845 | 4,870 | 4,767 | 8,941 | 11,532 |
| | 15% discount rate | 1,886 | 3,055 | 3,637 | 3,989 | 6,944 | 8,414 |
| **Medium/low variable scenario** | Zero discount rate | 438 | 38 | 941 | 491 | -273 | 2,173 |
| | 5% discount rate | 319 | 46 | 528 | 170 | -354 | 951 |
| | 10% discount rate | 228 | 35 | 302 | -78 | -452 | 272 |
| | 15% discount rate | 157 | 15 | 169 | -273 | -549 | -133 |
| **Low scenario** | Zero discount rate | -3,469 | -6,473 | -9,477 | -9,139 | -16,322 | -23,506 |
| | 5% discount rate | -3,066 | -5,104 | -6,701 | -8,175 | -13,049 | -16,868 |
| | 10% discount rate | -2,743 | -4,157 | -5,035 | -7,401 | -10,783 | -12,883 |
| | 15% discount rate | -2,479 | -3,480 | -3,978 | -6,771 | -9,166 | -10,356 |

*Indian rupee is equivalent to 0.01039 GBP (10.06.2020)

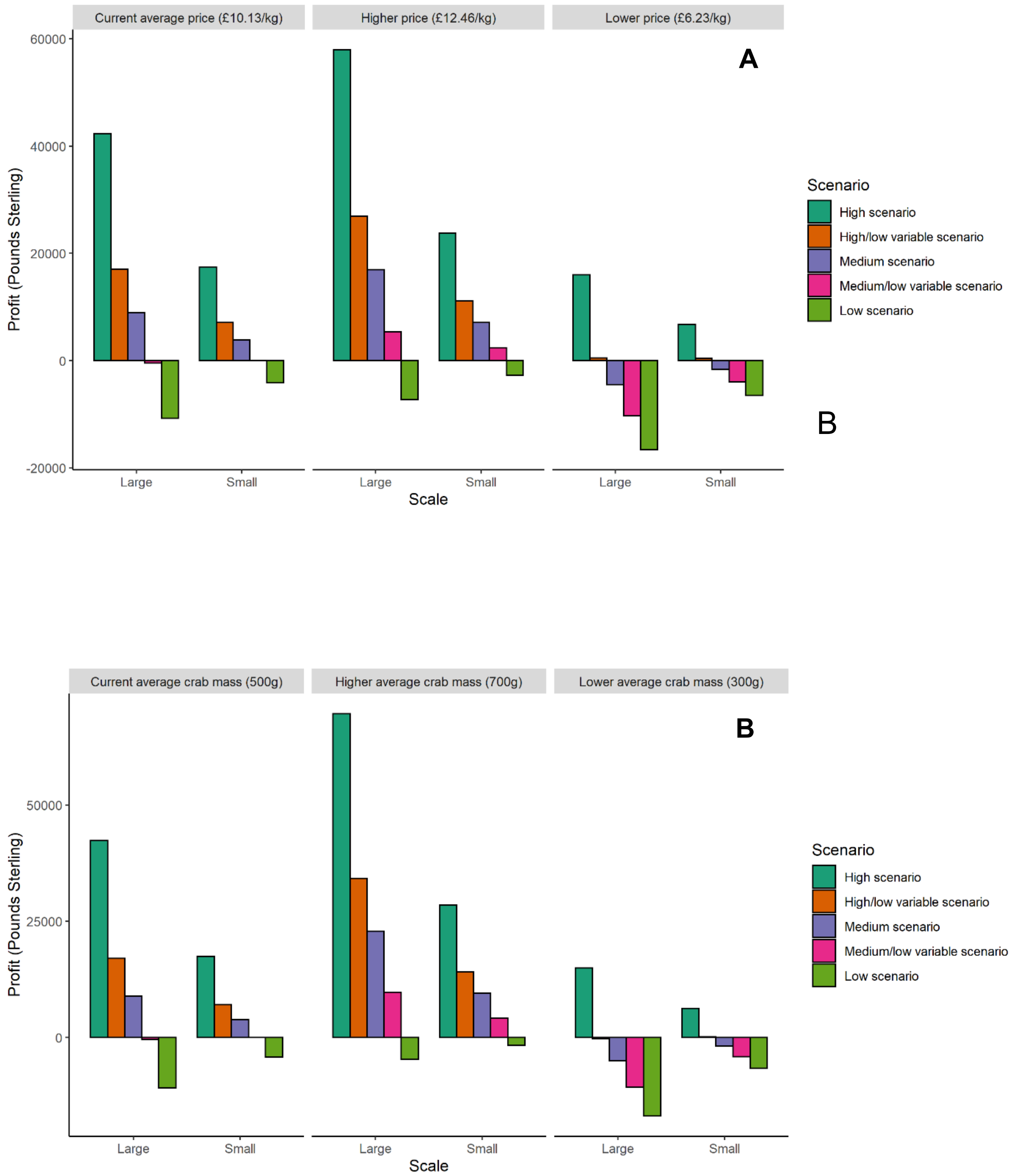


*Figure 3.5. Sensitivity analysis to changes in (A) market price per kilogram, (B) crab body mass. Calculated for NPV with a 10% discount rate after 10 years.*

## 3.4. Discussion

The adoption of the concept of sustainability to achieve overarching goals such as alleviating poverty and hunger has made governmental bodies, research institutes and individuals search for alternatives to well-known activities. Mud crab farming has been perceived as a feasible activity in South Asia for decades (e.g., Samonte and Agbayani, 1992) and with increased concerns of the sustainability of some aquaculture species such as prawns, it has gained significant attention as an alternative aquaculture species. Besides, sustainable farming can help conserving wild populations that have decreased as a result of overfishing due to high commercial value. Yet, to undertake small sustainable mud crab farming or any type of aquaculture, a number of resources are required. Thus, the present study aimed to identify what encourages and what limits mud crab farmers in Andhra Pradesh.

### 3.4.1. Limitations to mud crab farming

Mud crab farming can be established in both extensive and intensive systems. Extensive systems - keeping crabs in mangrove pens or other natural water bodies are common in Southeast Asia (Lindner, 2005) and the case of crab farmers using common water resources is a local example that mud crab farming can be incorporated into existing water bodies. Another way to sustainably farm crabs is rice paddy – crustacean co-culture (Halwart and Gupta, 2004). Availability of water resources is a significant advantage compared to other countries such as Tanzania (e.g., Mulokozi *et al.*, 2020) and Cambodia (e.g.

Richardson and Suvedi, 2018). Besides, Andhra Pradesh is well known for its intensive inland 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 rural communities who would benefit from livelihood diversification such as fishers that often do not possess more than their homestead land and is suffering from social inequality due to belonging to the minorities – the Scheduled Castes (SC), Scheduled Tribes (ST) or Other Backward Classes (Bakshi, 2008; Chauhan, 2008). The study presented in Chapter 2 on fisher communities in Karnataka showed that the lack of land was one of the main reasons why fishers were not considering undertaking mud crab farming. 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 enterprise that could also potentially have a positive contribution to mangrove and wild mud crab population conservation. While the land is not a ubiquitous limitation for the crab farmers that are already involved in this activity, 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). Furthermore, differences in land lease costs per one hectare indicate that communities could be affected by economies of scale – unit costs decrease with the increase of scale, thus 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, it could stimulate undertaking sustainable farming practices in existing water bodies, such as mangrove forests.

Another fundamental resource required for aquaculture is seeds and a technological breakthrough in the early 2000s (Quinitio *et al.*, 2001) made it possible to obtain hatchery reared mud crab juveniles. However, capacity and facilities differ greatly in the Indo-Pacific region. In India, up to date, there is only one working commercial mud crab hatchery with 2 million seed capacity providing for all the farmers in the country (P.R., personal communication), although plans of establishing a second mud crab hatchery have been made since the year 2017 (Sengupta, 2017; The Hindu Business Line, 2019). At the same time East African region still heavily relies only on wild seeds (Moksnes *et al.*, 2015a). Besides self-evident easing of pressure on wild populations, hatchery reared mud crab seeds are disease free and are the same size, which allows higher stocking density as cannibalism between same size individuals will be less likely (Lindner, 2005). Limited seed supply can be a potential source of further inequality as large-scale farmers more likely will be able to purchase seeds from hatcheries that are not nearby and cover travel costs. Furthermore, small-scale fishers and fish farmers often tend to be marginalised and not accounted for (Song *et al.*, 2018a). Results of this study confirmed that limited access to seeds currently is a barrier for the majority of mud crab farmers and the unpredictability has a significant economic impact.

One of the most controversial aspects of the whole aquaculture sector, including mud crab farming, is the use of so called “trash fish/low-value fish” as feed. The term trash fish commonly refers to the small-sized species with no or low commercial value and often to species that are not directly used for human consumption (Huntington and Hasan, 2009; Bunlipatanon *et al.*, 2014). Trash fish and bycatch are also used to produce fishmeal, a commercial product widely used in aquaculture/mariculture, land animal farming and pharmaceuticals (Shepherd and Jackson, 2013). As the aquaculture sector expands, the demand for fishmeal increases creating a ‘fishmeal trap’ – aquaculture is seen as an alternative to wild fish resources but at the same time is dependent on these resources (Wijkstrom and New, 1989; Ankomah-Yeboah *et al.*, 2018). Although the sustainability of fishmeal production requires its own discussion, it is clear from the results that mud crab farms heavily rely on “trash fish” – either as bycatch or as a targeted catch. However, most of these fish based on observation were sardines and tilapia - widely consumed nutritious fish. Therefore, taking into account, that it requires potentially thousands of kilograms of fish to feed one mud crab culture with an over 70% mortality rate for some farmers, it is important to question how sustainable the current practice of mud crab farming is and how it can be improved. Poor communities are not able to afford farmed fish and crabs and widely rely on more affordable wild caught fish, often those deemed “low value” (Joffre *et al.*, 2021). Yet, tilapia (here used as single species) is considered to be an invasive species in India that has escaped from the aquaculture farms into the wild (Singh, 2021), thus it could be argued that using tilapia as feed could help maintain the balance in wild fisheries. However, to determine that further and more complex research is necessary firstly, to assess the commercial value of the fish used as feed, secondly, to investigate people's preferences and thirdly, to conduct the stock assessment and future stock modelling.

Aquaculture at any scale involves various risks and having no access to subsidies and loans that could provide a safety cushion makes it even more difficult. Thus, it hinders community members who could potentially be interested in undertaking mud crab farming and also existing crab farmers to continue or expand crab aquaculture. Fisheries and small-scale aquaculture always have been a sector with poor access to institutional financial help such as credit. It was assessed in 2008 that 51.4% of farmer households did not have access to institutional and non-institutional credit (Rangarajan, 2008). No clear official statistics can be found regarding the situation currently, but it is believed that access to institutional credits for agriculture, fisheries and aquaculture is still relatively poor. Thus, microfinance is an essential tool for many in rural areas. Microfinance is a small-scale financial service, such as credits and savings for those who cannot access and/or afford formal credits (Robinson, 2001). In India, microfinance services could be obtained from microfinance institutions (MFIs) that are regulated by the Reserve Bank of India (RBI) and recently non-banking microfinance institutions have been recognised (Rangarajan, 2008; Ashaletha, 2018). Another important player in providing financial support for rural communities is the National Bank for Agriculture and Rural Development (NABARD) and especially linking bank services with self-help groups (SHGs). This highlights the importance of interactions between variables of the social-ecological system, in this case, between governance systems and actors. An example of SHG in the previous chapter showed higher financial, social and physical capital compared to those fishers that were not part of an SHG. However, such organisational structure might not be available in more remote areas or where crab farming is undertaken by only one person.

In May 2020 it was announced that as part of the relief package to mitigate COVID-19 impacts, USD 2.6 billion will be assigned to support the integrated, sustainable, inclusive development of marine and inland fisheries (Dao, 2020). More than a half will be dedicated to marine and inland fisheries, and aquaculture and the rest of it will be used to improve infrastructure, including fishing harbours and market development. However, priority has been given to marine fisheries and mariculture, thus again potentially excluding mud crab farmers, especially on a small scale as mud crab farming although relatively common and lucrative, is not perceived as important as shrimp or fish farming by the state. Although the contribution of small-scale aquaculture (FAO, 2009) and small-scale fisheries (Teh and Pauly, 2018) has been widely recognised, often it lacks evidence in the form of institutional support. Davis and Ruddle (2012) even argue that in the context of neoliberalism, support through co-management practices or other seemingly small-scale holder empowering approaches is not possible, as social and cultural values often in the core of smallholders, are not esteemed by neoliberalism. Thus, indicating that any financial and legislative governmental support will likely benefit large-scale practitioners and therefore non-institutional sector (e.g. NGOs, SHGs) is left to play an essential role in supporting smallholders.

### 3.4.2. Opportunities and feasibility of mud crab farming

The reason behind the success of the mud crab is rather simple – high market demand in both local and international markets. Small sub-adult crabs are often consumed by local communities themselves, while larger crabs are sold at hotels and restaurants for tourists (Mirera, 2011). In some places, such as the island of Kosrae, in the Federated States of Micronesia, *S. serrata* also has cultural value being an important part of family feasts or as gifts (Bonine *et al.*, 2008). A large share of literature is concerned with the international seafood trade to food surplus countries in the Global North that negatively impacts food insecure nations in the Global South from which good quality fish have been removed (e.g., Asche *et al.*, 2015; Golden, 2016). Yet, domestic demand arguably seems to be overlooked. A study based on FAO FishStat J Database showed that 85% of aquaculture production from the ten biggest aquaculture producer countries is consumed domestically and in India, this share is as high as 95% (Belton *et al.*, 2018). A study in India showed that demand for certain fish types depends on income group and technological advances in aquaculture are the key to an even wider availability to fish (Kumar *et al.*, 2005). It is difficult to trace where the production chain of the mud crab ends as there are no species-specific databases. Data sets on crabs might include marine crabs and data sets on crustaceans usually include shrimps and prawns that would account for the biggest share. The data from the International Trade Centre showed India is a net exporter of all types of crabs and crab products, with an annual growth of 18% and the main markets are China, Singapore, the United States of America, Taipei and Thailand (ITC, 2019). Yet, there is no clear data on the total amount of produce and what share stays in the domestic market. There is enough anecdotal evidence to support the importance of the domestic market in the trade of mud crabs, yet the lack of official data sets can render identifying any signs of market failure that can have a significant adverse impact on mud crab farmers.

The perception of mud crab farming was rather clear and unambiguous – it is a profitable, yet unsteady activity. However, the prospect of profit outweighed the unpredictability and even a complete loss of stock did not discourage farmers to continue. Thus, similarly to shrimp aquaculture, crab farming is 'like gambling' as several factors can influence the outcome, yet unlike gambling, shrimp farmers were found to be fully aware of risks and chose species, intensity and risk management plans accordingly (Joffre *et al.*, 2018). Therefore, flexibility regarding the type of culture (grow-out or fattening), stocking density and the length of culture and diverse source of income (especially for small-scale farmers) is their response to mitigate and/or adapt to risks.

The results of various scenarios showed that mud crab farming is a feasible income generating activity, however highly dependent on various factors such as market interest rate and market price that mud crab farmers cannot affect, and the survival rate of crabs that can partially be managed by monitoring and maintaining ponds. These findings coincide with other economic studies in Asia that have shown that mud crab fishing and farming is a lucrative business (e.g. Agbayani, 2001; Ferdoushi and Guo, 2010; Jahan and Islam, 2016). Meanwhile in East Africa, where selling prices are lower compared to Asia and the seed is limited as no commercial hatcheries have been established, profit is marginal and cage culture, in particular, can result in a significant loss (Moksnes *et al.*, 2015a).

The type of culture system is an important factor in determining the profit margin. For instance, cage culture is labour intensive as each animal is kept in an individual box, thus potentially having high labour costs. Theoretically, this culture practice should have the lowest mortality as cannibalism is completely excluded, but normally cage culture is used to obtain soft shell crabs (newly moulted crabs with a soft exoskeleton). Cage culture is a popular practice in Myanmar (FAO, 2003), the Philippines, Indonesia and Malaysia (Aquino, 2018). Monoculture using seeds has been reported to obtain the highest return on investment, followed by fattening (Agbayani, 2001; Marichamy and Rajapackiam, 2001). Mud crab aquaculture also has the potential to contribute to the whole country's economy such as in the case of India (Sathiadhas and Najmudeen, 2004), but as any intensive production, that could pose several challenges to sustainability such as the above mentioned use of "trash fish" as feed, which in turn can affect already marginalised and poor communities and the use of wild crablets in aquaculture as the commercial hatcheries cannot meet the demand Besides, mud crab aquaculture requires a high initial investment not depending on the scale of it, for instance, for pond preparation and feed for mud crabs (Jahan and Islam, 2016).

The survival rate was an important factor determining the profit of mud crab farming both for the small- and large-scale farmers. Although adult crabs are reported to be less susceptible to the main threat of shrimp aquaculture – white spot virus (WSV), yet can act as a carrier (Rajendranl, 1999; Somboonna *et al.*, 2010), cannibalism is a major issue and the main reason for low survival rates (Alberts-Hubatsch *et al.*, 2016). Several factors can determine survival rates and growth performance such as stocking density (Mann *et al.*, 2007), the use of shelter (Mirera and Moksnes, 2013; 2014) and whether crabs are kept in floating, bottom cages or outdoor tanks (Islam *et al.*, 2018; Mwaluma and Kaunda-Arara, 2021). This, therefore, indicates how complex and unpredictable mud farming is and that a collaboration between fishers, crab farmers, researchers and the aquaculture industry is required to address these various challenges. Besides, despite the assumptions based on research studies that WSV outbreaks might be rare, a major outbreak took place in S. serrata farms in Nagalayanka, Andhra Pradesh (CIBA, 2019), thus indicating that precautions must be taken to prevent the risks to infect crabs at their juvenile stage.

## 3.5. Conclusions

Mud crab farming as any aquaculture or agriculture activity involves risks and therefore it is important to assess whether the opportunities outweigh them. There is a significant initial investment potentially limiting local communities, it is a profitable activity for both small and large-scale mud crab farmers, yet only if at least a 23% survival rate is achieved each year. Mud crab farming is significantly influenced by a variety of factors and a mix of various issues can produce great losses. The main risks are associated with the limited supply of mud crab seeds, high mortality rates and the lack of any type of support from governmental or non-governmental organisations. There are no safety cushions, therefore in the case of a disease outbreak or extreme weather conditions, farmers will suffer a huge loss. Meanwhile, perceived as a delicacy with high nutritional value, mud crab has high demand in domestic and international markets, ensuring competitive prices compared to other aquaculture species.

The advantage of small-scale enterprises is their flexibility regarding culture practice – from fattening and grow-out in mangrove pens to cage culture, which would not suit large-scale farmers. Besides such small-scale aquaculture would be environmentally sustainable while still creating positive economic spillovers. Yet, it is important to address the issue with the use of nutritious and affordable fish as feed to produce economically more valuable produce. Therefore more research in collaboration with local communities, fishers and crab/fish farmers is essential to ensure environmental and social sustainability. This work, however, has shown that small sale mud crab farming has fewer risks and higher flexibility involved than large-scale mud crab farming and could be a feasible enterprise if innovative solutions to reduce mortality and alternative feeding regimes and/or resources are found. However, to make it more transparent and successful, support for sustainable small-scale aquaculture farms would be necessary as well as more detailed information on production chains and market values. This study also highlighted how closely connected social-ecological systems are as any changes in external market settings or climate patterns influenced actors, resource systems and resource units.

# Chapter four: Comparative analysis of the intestinal bacterial communities in mud crab *Scylla serrata* in South India

The adapted version of this chapter has been published as Apine, E., Rai, P., Mani, K. M., Subramanian, V., Karunasagar, I., Godhe, A. and Turner, L.M. (2021). Comparative analysis of the intestinal bacterial communities in mud crab *Scylla serrata* in South India. *Microbiology Open,* 10(2): e1179. https://doi.org/10.1002/mbo3.1179

## 4.1. Introduction

In complex social-ecological systems, socio-economic factors are only one facet of complex conditions that influence the choice of species captured and farmed. Biology and ecology are equally or, in some cases, even more, important as they can, for instance, determine the suitability of the species in the specific area and/or susceptibility to disease. One biological factor receiving increased attention related to the health status of animals is the gut microbiome. Studies on the gut microbiome of humans and other vertebrates have shown that the intestinal microflora is involved in various physiological processes such as development, nutrition and the immune response, including the production of vitamins and exogenous enzymes (e.g., Brestoff and Artis, 2013; Belkaid and Hand, 2014, Bäckhed *et al.*, 2004; Rowland *et al.*, 2018), all of which play an important role in maintaining the interior milieu of the host, and health. Whilst it has been hypothesised that the crustacean gut microbiome positively contributes to crustacean physiological and metabolic status (Cornejo-Granados *et al.*, 2018) and any disturbance in the delicate balance of the gut microbial composition can affect their susceptibility to pathogens (Shi *et al.*, 2019), still relatively little is known about the structure and function of the gut microbiome in this group.

The composition of the crustacean gut microbiome depends on several internal and external factors such as the development stage of the host (e.g. Rungrassamee *et al.*, 2013), host anatomy (e.g. Appril, 2017), environmental conditions that are either seasonal, or sudden and extreme events (e.g., prevalent rainfalls, increased temperature) as well as their habitat, and availability of feed (e.g. Sullam *et al.*, 2012; Xia *et al.*, 2014, Zhang *et al.*, 2017) and stress related to, for instance, territorialism (Moloney *et al.*, 2014). Studies on fish have shown that hatchery reared and/or captive fish microbiomes differ from their wild counterparts with reduced biodiversity or significantly different composition that potentially can lead to disadvantages to the host such as altered metabolic pathways and reduced immunity (e.g., Lavoie *et al.*, 2018; Salas-Leiva *et al.*, 2017; Ramirez and Romero, 2017). Determining the intestinal bacterial composition of mud crabs can identify functions that in case of dysbiosis (imbalance in the microflora) will be affected and thus require further investigation by applying various methods.

Resource units and resource systems determine how sustainable the social-ecological system is and any interventions by actors can alter it (Hinkel *et al.*, 2015). Besides, resource units and resource systems are constantly under the pressure of related ecosystems in terms of climate patterns and pollution. Thus, this study aimed to quantify how the geographical location (east or west coast of India), habitat (estuaries or aquaculture pond) and environmental conditions (salinity, temperature) impact gut microbial diversity and how it could be linked to the physiological status of the animal. The results will contribute to our knowledge of whether mud crab farming is a sustainable alternative to fishing without compromising animal health and what steps have to be taken to ensure this can continue in the future.

## 4.2. Materials and methods

### 4.2.1. Sample collection

Twenty four healthy male *S. serrata* crabs (with no signs of disease) were collected from the west and east coasts of South India. This included animals from the wild catch and also from crab farms. Crabs (n=3 from each sampling site (C1-3)) were collected from two sites (estuaries) representing wild samples (WW1-2, west coast and EW1-2, east coast) and two crab farms (WF 1-2, west coast and EF1-2, east coast) (Fig 4.1). Water temperature and salinity were recorded at each site (Table 4.1). Animals in both farms on the west coast from where samples were collected were fed with fresh bycatch, mainly sardines. Crabs on the east coast were fed with fresh tilapia in farm EF1 and dried sardines in farm EF2. Apart from the site EF2 where animals were fed a mix of probiotics, yeast and jaggery (unrefined cane sugar) once a month, no additives were given at the other farms. Crabs in the sites EF2, WF1 and WF2 were kept in earthen ponds, while site EF1 was connected to the estuary. The crabs were transported to the laboratory as soon as possible and subjected to cryoanaesthesia. After the measurement of weight and carapace width, the animals were thoroughly washed with sterile water and disinfected with 75% ethanol for 2-3 minutes. The animals were dissected using sterile lancets and the gut (midgut and hindgut) was separated using sterile forceps and immediately placed in sterile 1.5 mL microcentrifuge tubes. All dissecting tools were alcohol flame sterilized between dissecting each individual sample. Samples were stored at -80 °C until further analysis.

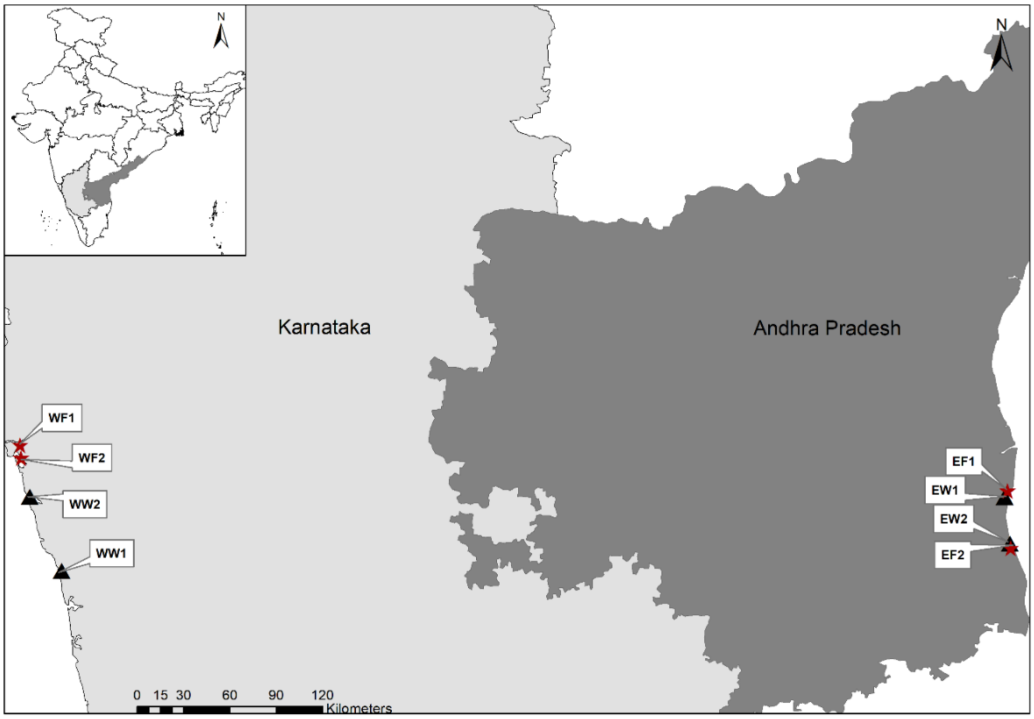


*Figure 4.1. Sampling sites: triangle - wild sites, star – farms. WF – west coast farm, WW – west coast wild site, EF – east coast farm, EW – east coast wild site. Three crabs (C1-C3) were collected from each sampling site.*

*Table 4.1 Characteristics of sampling sites and crabs.*

| Sample ID | Coast | Site type | Latitude | Longitude | Temperature (°C) | Salinity (ppt) | Crab mass (g) | Carapace width (mm) |
|---|---|---|---|---|---|---|---|---|
| **WW1** | West | Wild | 13°50’53.52” N | 74°37’52.089” E | 30 | 27 | 450.88±98.55 | 140.00±14.79 |
| **WW2** | West | Wild | 14°16’47.496” N | 74°26’37.679” E | 29 | 33 | 699.56±215.63 | 160±17.32 |
| **WF1** | West | Farm | 14°34’26.364” N | 74°22’28.938” E | 28 | 35 | 148.93±30.54 | 91.33±4.93 |
| **WF2** | West | Farm | 14°30’19.296” N | 74°23’38.151” E | 27 | 10 | 815.26±33.15 | 158.00±2.00 |
| **EW1** | East | Wild | 14°16’43.86” N | 80°7’19.436” E | 31 | 21 | 200.00±164.62 | 109.00±29.51 |
| **EW2** | East | Wild | 14°0’24.948” N | 80°9’10.411” E | 30 | 33 | 103.33±40.41 | 87.33±10.11 |
| **EF1** | East | Farm | 14°18’48.168” N | 80°8’20.893” E | 27 | 27 | 366.66±81.44 | 130.00±6.55 |
| **EF2** | East | Farm | 13°58’46.272” N | 80°9’27.586” E | 35 | 36 | 190.00±52.91 | 101.33±4.16 |

### 4.2.2. DNA extraction, PCR amplification and sequencing of 16S rRNA amplicon

Total DNA from gut samples was extracted using the QIAamp DNA Stool Mini Kit (QIAGEN, Germany) and DNeasy PowerSoil Kit (QIAGEN, Germany) following the manufacturer's instructions. Intestines were firstly lysed in InhibitEX Buffer and then purified on QIAamp spin columns. Purification includes digesting proteins with Proteinase K, binding DNA to the QIAamp silica membrane, washing away impurities and eluting pure DNA from the spin column with water. The quality and quantity of extracted DNA were determined in a NanoPhotometer N60 (Implen, Germany). Samples were stored at -20 °C until amplification.

The 16S rRNA gene was then amplified using forward primer 16F- 5' AGAGTTTGATCMTGGCTCAG 3' and the reverse primer 16R- 5' TACGGYTACCTTGTTACGACTT 3'. The PCR mixture contained high-fidelity DNA polymerase, 0.5 mM dNTPs, 3.2 mM $MgCl_2$ and PCR enzyme buffer, 40 ng of extracted DNA and 10 pM of each primer. The reaction conditions included an initial denaturation at 95$^o$C for 3 minutes followed by 25 cycles each of denaturation at 95$^o$C for 15 seconds, annealing at 60$^o$C for 15 seconds and elongation at 72$^o$C for 2 minutes followed by a final extension at 72$^o$C for 10 minutes. The PCR products were purified using QIAGEN GEL Purification Kit (QIAGEN, Germany). The amplified products were outsourced for the library preparation and Oxford Nanopore Technology (ONT) 1-D sequencing using GridION device to the Biokart India Pvt. Ltd., Bangalore, India according to the manufacturer's instruction. Briefly, amplicons were purified using QIAGEN Gel Purification Kit (QIAGEN, Germany). DNA concentration was estimated by using a Qubit dsDNA HS assay kit and Qubit 4.0 Fluorometer (ThermoFisher Scientific, USA). Purified PCR products from each sample were end-repaired and dA tailing using NEBNext Ultra II End Repair/dA-Tailing Module (New England Biolabs, USA) was performed according to the protocol described by the manufacturer. The dA tailed PCR products were ligated with barcode adaptors using the Oxford Nanopore Native Barcode kit (EXP-PBC096) and the Oxford Nanopore 1D Ligation Sequencing kit (SQK-LSK109). The DNA library was loaded into a flow cell for 24-48 h run on the GridION portable sequencer for sequencing (Oxford Nanopore Technologies, UK).

### 4.2.3. Data analysis

After base calling raw FAST5 files, trimming and alignment of the reads along with the operational taxonomic unit (OTU) picking was performed using GAIA 2.0 workflow (Paytuvi *et al.*, 2017). The length of the sequences varied mainly between 100 and 1600 base pairs. Sample WF2C1 was excluded from further analyses as it was a statistically significant outlier due to low quality reads according to Grubb's test ($p<0.05$). Alpha diversity and beta diversity at the genus level were calculated in PAST (Hammer *et al.*, 2001). METAGENassist (Arndt *et al.*, 2012) was used to map OTUs to phenotype. Statistical analyses and plotting were carried out in PRIMER-E (Clarke and Gorley, 2006) and the R Studio using Bray-Curtis similarity of square root transformed data. The genera abundant less than 1% were combined in the group designated as 'Other'. Values of $p < 0.05$ were considered significant (95% confidence interval). SIMPER test was used to calculate (dis)similarity between groups using the average of Bray-Curtis dissimilarity. An unconstrained hierarchical divisive clustering routine UNCTREE was used to cluster samples based on alpha diversity. Distance based linear model (DistLM) in PRIMER-E and permutational multivariate analysis of variance (PERMANOVA) using community ecology package ‘vegan’ in the R Studio (Oksanen *et al.*, 2017) were chosen to evaluate the significance of environmental parameters, crab mass and carapace width, geographical location and type. The Chi-square test was used to assess associations between alpha biodiversity indices and variable factors.

The sequence data have been deposited in the sequence read archive (SRA) at National Center for Biotechnology Information (NCBI; Bethesda, MD, USA) under BioProject PRJNA691201, BioSample accession numbers are SAMN17283444 - SAMN17283464.

## 4.3. Results

### 4.3.1. The composition of the gut

The 16S rRNA amplicon sequencing on Nanopore GridION generated a total of 530,355 operational taxonomic units (OTUs), of which 32% were unknown. Acquired OTUs were assigned to 19 phyla, 45 classes, 88 orders, 160 families, 317 genera and 430 species. The OTUs were assigned to five main phyla: Proteobacteria (51.8% ± 9.7%), Actinobacteria (10.9% ± 8.3%), Cyanobacteria, (7.3% ± 4.2%) Firmicutes (4.6% ± 1.1%) and Bacteriodetes (3.2% ± 0.8%); five classes: *Betaproteobacteria* (43% ± 12%), *Alphaproteobacteria* (5.7% ±1.6%) , *Actinobacteria* (5.1% ± 3.9%), *Bacilli* (4.1% ±1.4 %) and

*Rubrobacteria* (3.3% ± 2.0%) ; five major genera: *Massilia* (25% ± 11.5%), *Pseudoduganella* (8.1% ± 3.5%) , *Microcoleus* (4.3% ± 2.3%), *Bacillus* (3.1% ± 1.0%) and *Gaiella* (2.9% ± 1.4%) (Fig.4.2). On the species level, OTUs were assigned to five main species*: Massilia albidiflava* (25.2% ±7.3%), *Massilia* sp. NCCP 1146 (2.6% ± 0.4%), *Microcoleus* sp. HTT-U-KK5 (2.6% ± 1.6%), *Pseudoduganella violaceinigra* (9.3% ± 2.1%) and *Aciditerrimonas ferrireducens* (1.4% ± 0.9%). Further analyses, however, are performed on the genus level as an assignment to species varies, depending on a similarity threshold. Besides some of the species are novel isolates that have not yet been widely described, such as *Massilia* sp. NCCP 1146 and *Microcoleus* sp. HTT-U-KK5. Genera that are widely used in probiotics such as *Lactobacillus* and *Pseudoalteromonas* comprised less than 0.1% and 0.5%, respectively, of the gut microbiome. In addition, crabs from the farm where probiotics were given once a month (EF2) had the lowest average abundance of *Lactobacillus* and *Bacillus*, but a slightly higher abundance of *Pseudoalteromonas* compared to the rest of the groups.

The SIMPER analysis showed that the greatest dissimilarity of OTUs present in our eight sampling sites was between farms on the east coast EF1 and EF2 (62.53%) and the farm on the east coast and the wild site on the west coast EF2 and WF2 (64.36%). Examining the similarity between wild and farmed animals, it was seen that OTUs varied more in wild animals (66.20% similarity within the group) than in the pond cultivated animals (71.39% similarity within the group). That was also confirmed by the similarity within the sampling sites, where wild sites had less similarity (Table 4.2).

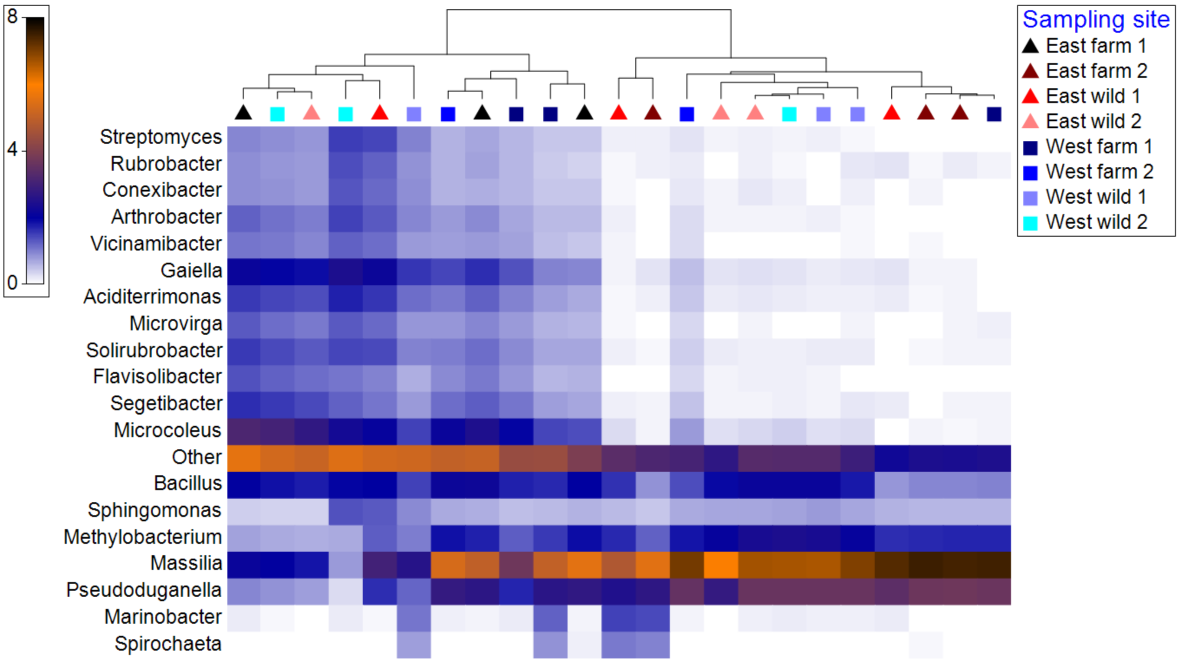


*Figure 4.2. Shade plots of relative abundance of operational taxonomic units OTUs (%) assigned to 20 most abundant genera of individual crab gut microbiomes from 8 different sampling sites. Triangles represent east coast samples and squares represent west coast samples. The samples are clustered with unconstrained hierarchical divisive clustering routine UNCTREE. The relative abundance is square root transformed. The taxa present less than 1% are combined under 'Other'.*

*Table 4.2. The average similarity of OTUs within sampling sites based on Bray-Curtis dissimilarity.*

| **Average similarity within groups (%)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **EF1** | **EF2** | **EW1** | **EW2** | **WF1** | **WF2** | **WW1** | **WW2** |
| 72.34 | 73.46 | 39.52 | 45.95 | 54.26 | 65.99 | 53.62 | 45.07 |

Geographical location or habitat (wild or pond cultivated) did not have a significant impact on gut microbial biodiversity. On the other hand, a distance based linear model (DistLM) showed that temperature had a statistically significant effect on the OTU abundance (%) at the genus level ($p=0.018$). There was a slight trend of decreased OTU richness with increasing temperature (Fig.4.3). This was confirmed by PERMANOVA ($p=0.032$). However, salinity, crab mass and carapace width were not statistically significant ($p>0.05$). Calculated alpha diversity analysis showed that the number of bacterial genera found in mud crab guts varied from 92 (EF2C1) to 289 (WW1C3). While the temperature was the only statistically significant factor that affects Shannon's diversity index (H) that accounts for both species richness and abundance, the number of taxa alone is also significantly affected by the coast ($p=0.0117$) and the interaction between crab body mass and carapace width ($p=0.0231$).

Although microbial composition varied between individuals, all animals from the site EF1 presented consistently high OTU richness and evenness. Yet, in the case of the second farm on the east coast EF2, the lowest OTU richness and evenness (Table 4.3) were obtained. Samples were clustered based on the alpha diversity indices using unconstrained hierarchical divisive clustering routine UNCTREE and two main clusters were obtained (Fig.4.4). Only samples from EF1 and EF2 were grouped together but in the opposite main groups.

*Table 4.3. Alpha diversity indices for individual animals at the genus level. Simpson's index (1-D) indicates evenness, Shannon's diversity index (H') accounts for both species richness and abundance, Buzas and Gibson's evenness index ($e^H/S$) implies evenness, Chao1 estimates based on the abundance of less present taxa.*

| | Number of taxa | Individuals | Simpson 1-D | Shannon H | Evenness $e^H/S$ | Chao-1 |
|---|---|---|---|---|---|---|
| **EF1C1** | 215 | 13299 | 0.9589 | 4.05 | 0.2669 | 218 |
| **EF1C2** | 245 | 15040 | 0.7343 | 2.521 | 0.05076 | 251.3 |
| **EF1C3** | 244 | 19057 | 0.879 | 3.377 | 0.1201 | 248.2 |
| **EF2C1** | 92 | 15504 | 0.4555 | 1.109 | 0.03294 | 99.5 |
| **EF2C2** | 95 | 15635 | 0.452 | 1.111 | 0.03198 | 107.7 |
| **EF2C3** | 125 | 11575 | 0.6277 | 1.923 | 0.05474 | 137.7 |
| **EW1C1** | 158 | 11594 | 0.7624 | 2.5 | 0.07707 | 182.5 |
| **EW1C2** | 281 | 14622 | 0.965 | 4.228 | 0.2441 | 291 |
| **EW1C3** | 57 | 3144 | 0.4295 | 1.05 | 0.05014 | 72.4 |
| **EW2C1** | 112 | 6508 | 0.6009 | 1.67 | 0.04744 | 149.1 |
| **EW2C2** | 143 | 12590 | 0.6397 | 1.804 | 0.04249 | 174.7 |
| **EW2C3** | 252 | 18948 | 0.9579 | 4.072 | 0.2329 | 258.1 |
| **WF1C1** | 83 | 9338 | 0.4551 | 1.117 | 0.03682 | 99.5 |
| **WF1C2** | 246 | 12184 | 0.8933 | 3.502 | 0.1349 | 252.7 |
| **WF1C3** | 262 | 14370 | 0.802 | 2.995 | 0.07626 | 263.8 |
| **WF2C2** | 251 | 15716 | 0.8471 | 3.195 | 0.09721 | 259.7 |
| **WF2C3** | 185 | 13056 | 0.5497 | 1.587 | 0.02642 | 222.6 |
| **WW1C1** | 133 | 15533 | 0.5723 | 1.556 | 0.03563 | 177 |
| **WW1C2** | 145 | 15569 | 0.6444 | 1.813 | 0.04227 | 178.2 |
| **WW1C3** | 289 | 13056 | 0.9627 | 4.3 | 0.2549 | 292.7 |
| **WW2C1** | 141 | 18257 | 0.6429 | 1.801 | 0.04295 | 153.2 |
| **WW2C2** | 253 | 13369 | 0.9578 | 4.094 | 0.2371 | 263.9 |
| **WW2C3** | 256 | 19567 | 0.973 | 4.337 | 0.2988 | 265.8 |

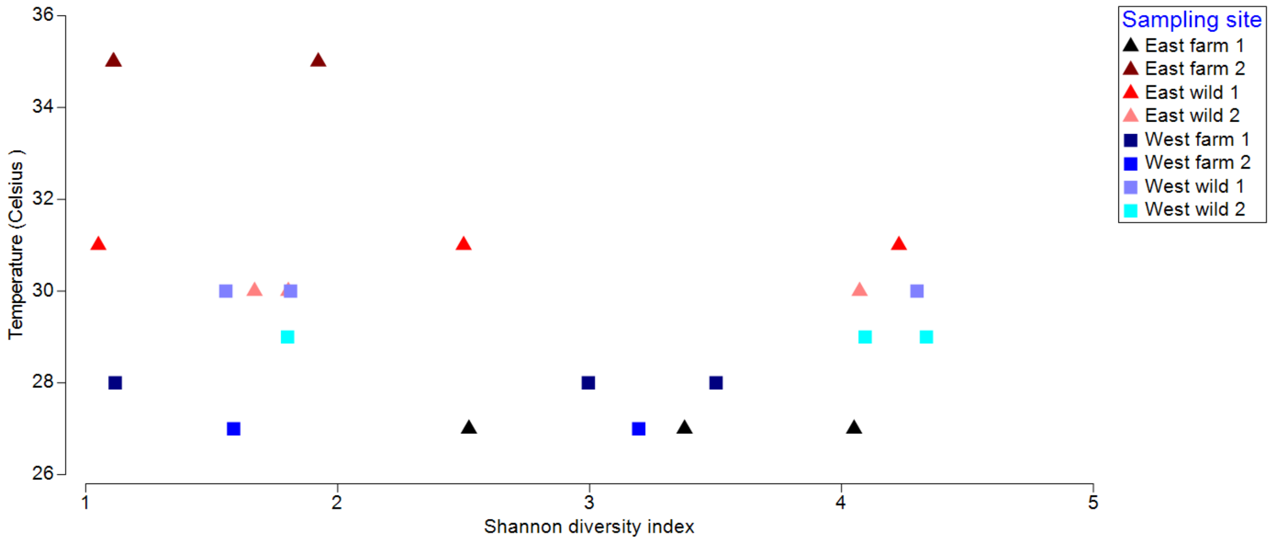


*Figure 4.3. Shannon's diversity index (H') at the genus level of individual crab gut microbiomes from 8 different sampling sites plotted against the temperature of their sampling sites. Triangles represent east coast samples and squares represent west coast samples. The samples EF2C1 and EF2C2 have similar Shannon diversity index, thus have overlapped and appear as one triangle. A higher number indicates higher biodiversity based on the OTU abundance and richness. The results of the distance based linear model showed that temperature had a statistically significant effect on the OTU abundance (%) at the genus level (p=0.018).*

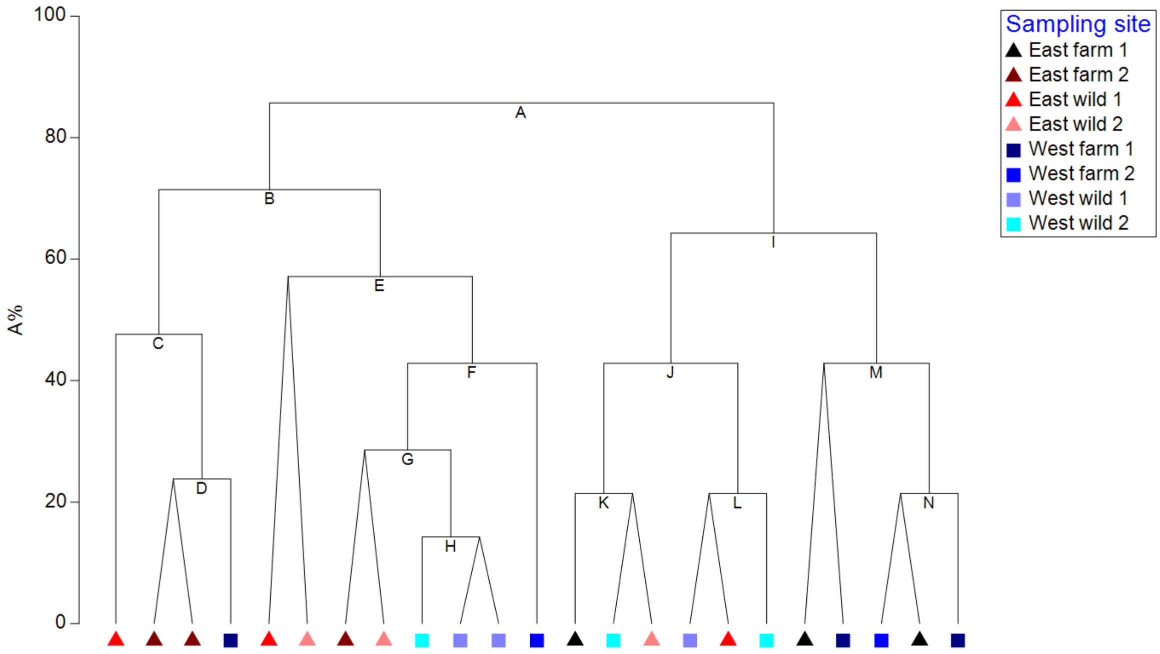


*Figure 4.4. Unconstrained hierarchical divisive UNCTREE clusters based on alpha diversity indices of individual crab gut microbiomes at the genus level. Triangles represent east coast samples and squares represent west coast samples. The dendrogram is plotted against an arbitrary equi-stepped scale (A%) in which the divisions sum up to 100.*

### 4.3.2. Phenotypic characterisation of the gut microbiome

Obtained OTUs were mapped to phenotypic categories with the help of METAGENassist. Approximately 7% of bacteria found in crabs from sites EF1, EW2 and WW2 are potential human pathogens. However, enteric bacteria derived from the gut of warm-blooded animals and pathogenic genera like *Salmonella* were less than 0.1 % and *Staphylococcus* and *Streptococcus* were less than 0.8%. Besides, no crab pathogens such as *Aeromonas, Rickettsia* and *Spiroplasma* were found in any of the samples. Less than 0.1% of OTUs were identified as *Vibrio parahaemolyticus*.

Only between 8 to 22% of OTUs on an individual level could be mapped to a specific metabolic pathway. By mapping OTUs to phenotypic characteristics, ammonia oxidation, dehalogenation, sulphate reduction, nitrite reduction, and sulphide oxidation were found to be the main five metabolic processes the mud crab gut microbiome is involved in. (Fig.4.5). A very low percentage of lignin degraders were mapped to wild crab samples only. Other metabolic processes identified included iron oxidation, lignin degradation, selenate reduction, sulphur reduction and storage of polyhydroxybutyrate. PERMANOVA showed that temperature ($p=0.029$) and habitat ($p=0.038$) significantly affected differences between animals, yet coast and salinity were not statistically significant.

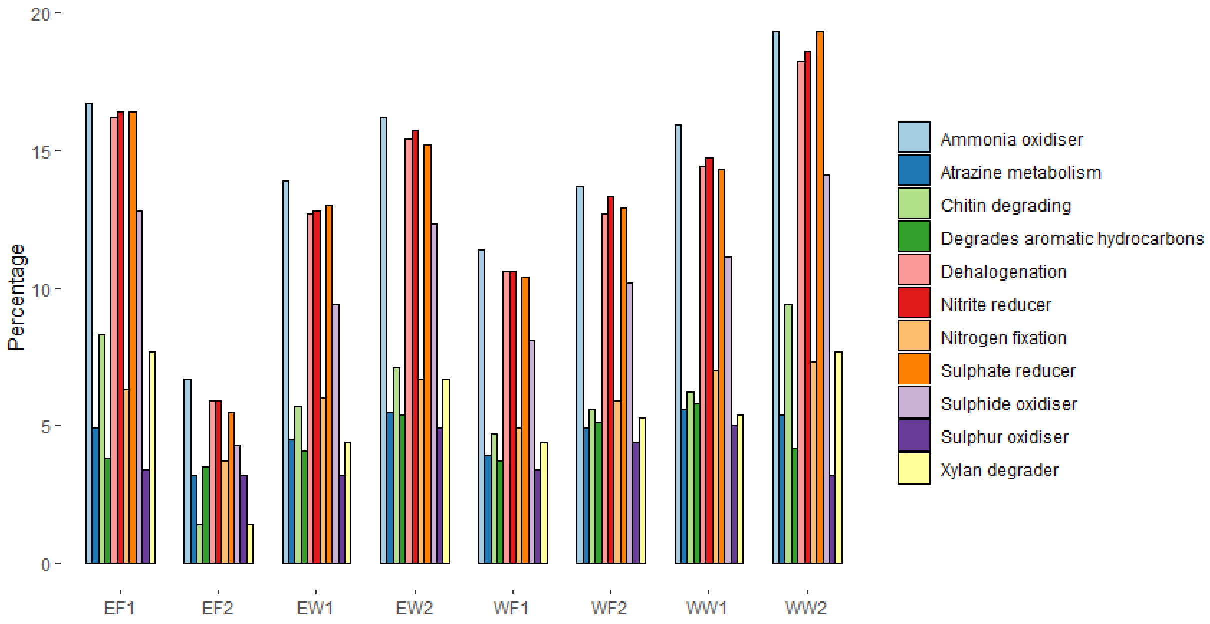


*Figure 4.5. This figure indicates eleven main metabolic processes in which gut bacteria of mud crabs were involved. Operational taxonomic units OTUs were mapped to phenotypic characteristics with the help of METAGENassist. The results shown, are the average for the sampling site, no individual data were given. To be recognised as one of the eleven main metabolic processes, 5% of OTUs of at least one sample had to be assigned to the process.*

## 4.4. Discussion

Due to the recognised contribution of the intestinal microbiome to host health, it is essential to assess the bacterial composition of aquaculture species as it plays a significant role in determining their physiological status. Moreover, the health status of resource units can affect the whole social-ecological system through the connections between the components. The bacterial diversity and abundance are affected by various parameters such as habitat, feed, water quality and physicochemical factors, including temperature and salinity. The state of Andhra Pradesh on the east coast is warmer and has a different monsoon weather pattern than Karnataka on the west coast; therefore there could be differences in the gut microbiome between the coasts due to temperature effects. Besides, crabs cultured in farms, as opposed to wild caught, are likely to have less diverse food sources which could have a direct impact on intestinal bacterial diversity. Furthermore, while intestinal bacterial communities using next generation 16S rRNA amplicon sequencing or clone library analysis and denaturing gradient gel electrophoresis (DGGE) have been performed on *S. paramamoisam* (Li *et al.*, 2012; Deng *et al.*, 2019; Wei *et al.*, 2019), this is the first study to explore the gut microbiome of *S. serrata* using 16S rRNA amplicon sequencing.

The most common phyla in the *S. serrata* gut microbiome were Proteobacteria*,* Actinobacteria*,* Cyanobacteria*,* Firmicutes and Bacteriodetes, while the studies on *S. paramamoisam* from China found Fusobacteria and Tenericutes to be among the core gut microbiome phyla (Li *et al.*, 2012; Deng *et al.*, 2019; Wei *et al.*, 2019), which were not found in the samples of this study.

Fusobacteria, Gram-negative obligate anaerobic bacilli are mainly associated with the oral microbiome of humans, (e.g., Kostic *et al.*, 2012; Kelly, Yang and Pei, 2018; Saito *et al.*, 2019). Tenericutes, Gram-negative obligate cell-associated bacteria have been found in all vertebrate guts examined. Although it is recognised to be one of the least abundant phyla in mammalian gut microbiotas, it has been found in dolphins in relatively high proportions (Bik *et al.*, 2016). Interestingly, it is one of the most abundant phyla in the gut of the Chinese mitten crab, *Eriocheir sinensis* (Zhang *et al.*, 2016; Ding *et al.*, 2017; Dong *et al.*, 2018). In one study on the meta-analysis of marine and freshwater shrimp microbiota, Tenericutes and Fusobacteria were twenty five and five times respectively, were more abundant in marine shrimps compared to freshwater shrimps (Cornejo-Granados *et al.*, 2018). Estuaries in south India are subject to highly variable salinity due to the heavy monsoon, which can vary from 0 to 35 ppt (Shruthi *et al.*, 2011; Ramachandra *et al.*, 2013), and this could possibly explain the absence of these two phyla in the *S. serrata* gut microbiome. Although variations in the gut microbial composition in different geographical locations are often explained by the differences in the diet and behaviour, and not by the location per se (Ye *et al.*, 2014), it is not clear how these differences could affect animal health if crab seeds would be imported to India, in this instance, from China. Further research is required to determine differences in gut microbial composition at different development stages and whether changes in diet and environmental factors induce any alterations, and what the implications on the host's physiology are.

Proteobacteria, Firmicutes, Bacteriodetes and Actinobacteria comprise core components of the gut microbiome in humans (Lawley and Walker, 2013; Hugon *et al.*, 2015), fish (e.g., Sullam *et al.*, 2012; Sandve *et al.*, 2017) and crustaceans. However, the crustaceans have fewer Actinobacteria (e.g., Zhang *et al.*, 2014a, 2016; Ding *et al.*, 2017; Dong *et al.*, 2018; Shi *et al.*, 2019) when compared to the other three groups. The abundance of Cyanobacteria in the gut could be linked to the host trophic level. A study on fish with different diets showed Cyanobacteria to be abundant in filter-feeding fish, less in herbivorous and omnivorous fish and very little in carnivorous fish (Liu *et al.*, 2016). *Scylla serrata* juveniles and small adult crabs (up to 99 mm CW) are omnivorous, whereas middle- and large-sized crabs are top benthic predators, opportunistic scavengers and exhibit cannibalistic behaviour (Brown, 1993; Alberts-Hubatsch *et al.*, 2016). Further, Cyanobacteria is prone to bloom in response to eutrophication or increased temperature and may produce cyanotoxins that can be harmful to the animal and accumulate in the food chain (Ferrão-Filho and Kozlowsky-Suzuki, 2011). There was no pattern of presence/absence based on the location or type. No Cyanobacteria were found in the guts of animals from the farm EF2, where crabs were fed with dried fish and probiotics once a month. This suggests that the pond water contained little or no Cyanobacteria and that they were not obtained via feed.

At the genus level, *Massilia, Bacillus, Microcoleus, Pseudoduganella* and *Gaiella* were found to be the most abundant in the mud crab gut microbiome. *Massilia* and *Pseuduganella* belong to the family *Oxalobacteraceae* of the phylum Proteobacteria, while *Microcoleus* belong to Cyanobacteria, *Bacillus* to Firmicutes and *Gaiella* to Actinobacteria. *Gaiella* has mainly been reported in soil and in association with roots (Hernández *et al.*, 2015; Song *et al.*, 2018b; Zeng *et al.*, 2018), which suggests that they might not be resident bacteria, but are continuously obtained through scavenging on the benthos. Studies on *S. serrata* in India on cultivable bacteria from the gut using conventional culture techniques found *Micrococcus, Coryneforms, Vibrio, Pseudomonas, Aeromonas, Achrobacter, Flavobacterium* and *Enterobacterium* (Rameshkumar *et al.*, 2009), *Shewanella, Acinetobacter, Bacillus* and *Cytophaga* (Lalitha and Thampuran, 2012) to be the most abundant. In another study, pathogenic bacteria such as *Staphylococcus aureus*, *Escherichia coli,* and *Vibrio* sp. were abundant in mud crab guts sampled from south India (Krishna *et al.*, 2016). The very low abundance of *Enterobacterium* and *Escherichia* (<0.1%) indicates that no raw or treated sewage is let into the estuaries or ponds. *Vibrio* spp. accounted for less than 0.1% indicating that these are not a significant component of the gut flora of crabs. *Vibrio* spp. is very common in the aquatic environment and the gut microbiome of fish (Egerton *et al.*, 2018), shrimps (Rungrassamee *et al.*, 2013, 2014; Md Zoqratt *et al.*, 2018) and lobsters (Ooi *et al.*, 2017), only a few species are pathogenic with most others being normal flora of the gut environment and some may even have a probiotic effect (Gomez-Gil *et al.*, 2000).

The relatively high abundance of *Bacillus* could indicate that at the time of sampling the crabs were healthy and there was no dysbiosis as *Bacillus* spp. have been reported to secrete compounds and antimicrobial molecules beneficial to the host that protect it against pathogens (Ilinskaya *et al.*, 2017). Although less than *Lactobacillus* spp., some species of *Bacillus* are used as probiotics for cultured fish and shrimps and have been shown to have significant immunomodulatory effects such as increased disease resistance of the host and consequently improved survival (Cha *et al.*, 2013; Tarnecki *et al.*, 2019). The type of catch (wild or farmed) or coast location did not affect the abundance of *Bacillus*.

Yet, it was three times less abundant in the farm EF2, where the temperature on the sampling day was > 35°C, although *B. subtilis* is reported to have unaffected growth in temperatures as high as up to 76°C (Warth, 1978).

Studies on the gut microbiome of aquatic animals and especially fish show that variables determining resource units, such as trophic level, season, development, sex, habitat and life stage are among the factors affecting the composition of the gut microbiome at the interspecies level (Butt and Volkoff, 2019). However, high individual variability of the crustacean gut microbiome within groups shown by other studies (e.g., Li *et al.*, 2007; Ding *et al.*, 2017; Wei *et al.*, 2019) was observed in this study too and could be explained by the fact that *S. serrata* is an omnivorous and opportunistic scavenger. No significant differences in the gut microbiome between wild and pond-cultivated crabs were found and these results are similar to the studies on *Eriocheir sinensis* (Li *et al.*, 2007) and black tiger shrimp *Penaeus monodon* (Rungrassamee *et al.*, 2014). On the other hand, higher diversity and higher bacterial load were observed in wild *S. paramamoisam* crabs than in the healthy and diseased pond-raised crabs (Li *et al.*, 2012). It would have been interesting to compare healthy crabs collected from the same ponds or farms as diseased crabs, to see if their health and immune system were already compromised leading to changes in the gut bacterial diversity. However, it is difficult to predict the wild catch, and disease outbreaks in farms happen relatively seldom.

The similarity between groups suggests that environmental conditions of related ecosystems might play an essential role in forming the gut microbiome (Fraune and Bosch, 2007). Furthermore, there is no formulated feed for *S. serrata* and the use of probiotics is not common; therefore wild and pond raised crabs are more likely to have a similar diet. Significantly, crabs from the only farm where probiotics were used once a month, had lower bacterial diversity. That farm, however, was also the only farm where crabs were fed with salt-dried fish as compared to crabs fed with fresh fish in the other farms. Salted and dried fish are known to contain very low levels of bacteria when compared to fresh fish as they have a low water content that does not support the growth of most organisms. Although the bacterial profile of the probiotic used in this farm was not known, a slightly higher abundance of *Pseudoalteromonas* compared to the rest of the groups indicates that they may contain bacteria of this genus. Yet, at the same time, this farm also had the highest water temperature on the day of sampling and our results showed that temperature is a significant factor influencing gut microbiome diversity. Thus, it is difficult to conclude whether salted and dried fish significantly reduce gut microbial diversity, and more replicates would be necessary to prove this hypothesis. However, crab farmers in India have acknowledged rising temperatures that have been observed in recent years as one of the threats and reasons for crab mortality (E.A., personal communication). Elevated water temperature has been shown to significantly reduce the bacterial diversity in the gut of mussels *Mytilus coruscus*, yet simultaneously increase the abundance of opportunistic bacteria, such as *Bacteroides* and *Arcobacter*, which could result in higher host susceptibility to disease (Li *et al.*, 2018). Furthermore, the diversity of planktonic bacteria has been found to decrease in the Atlantic Ocean towards the equator (Milici *et al.*, 2016). Thus, as the sea surface temperature (SST) is predicted to increase (IPCC, 2014), changes in the crab gut microbiome negatively affecting the physiological and immune status of crabs could be expected. This could be detrimental to crabs facing the twin threats of increasing SSTs and increasing pathogen levels such as *Vibrio* spp. which prefers warm temperatures (Semenza *et al.*, 2017). Yet, the temperature is only one of multiple environmental factors that could determine microbial richness and abundance, thus more detailed studies considering various physiochemical data are required to understand the role of water temperature in altering the gut microbiome (Thompson *et al.*, 2017).

By mapping OTUs to phenotypic characteristics, it was found that ammonia oxidation, dehalogenation, sulphate reduction, nitrite reduction, sulphide oxidation are the main five metabolic processes the mud crab gut microbiome is involved in. Besides ammonia oxidation and nitrite reduction, bacteria were also found to be fixing nitrogen, indicating that these processes could be part of nitrogen cycling. As almost none of the OTUs were assigned to ammonia-oxidizing bacteria (AOB) such as *Nitrosphira, Nitrosomonas* and *Nitrosococcus* (Burrel *et al.*, 2001; Braker and Conrad, 2011), it can be assumed that the majority of nitrogen fixation, ammonia oxidation and nitrite reduction in the guts of *S. serrata* is performed by Cyanobacteria (Andriesse *et al.*, 1990; Herrero *et al.*, 2001). Besides, *B. subtilis* found in soils has also been reported to be involved in nitrogen fixation (Beneduzi *et al.*, 2008; Hashem *et al.*, 2019) and *Bacillus* was one of the main genera found in the crab gut. Ammonia, nitrite and nitrate are common and essential components in the aquatic environment, yet elevated levels can be toxic to aquatic animals (Romano and Zeng, 2013). Therefore, the results indicate that gut bacteria are strongly involved in mineralization by processing these compounds to avoid toxic effects. Microbial oxidation of sulphur is carried out to produce energy that is further used for synthesizing their structural components and it is possible that *Bacillus* (Friedrich *et al.*, 2001) and *Microcoleus* (possibly *Microcoleu*s sp. HTT-U-KK5) (Fike *et al.*, 2016) in these samples perform these tasks.

Studies on plant communities have shown that higher alpha diversity increases resistance to invasive species, in particular to those similar to the residents (Fargione *et al.*, 2003; Xu *et al.*, 2004; Fargione and Tilman, 2005). Studies on aquatic animals indicate that diseased animals have lower gut bacterial diversity and total abundance (Li *et al.*, 2012) which does not augur well for the health of the animals. This is believed to be due to colonisation resistance, a theory that can be defined as the resistance of the gut microbiome to colonisation by exogenous pathogens or inhabitation of overgrowth of commensal bacteria that are opportunistic pathogens (Lawley and Walker, 2013; Pickard *et al.*, 2017; Iacob *et al.*, 2019). Although this concept concerning the gut is mainly discussed within the human and mammalian context, lately it has also been applied to fish aquaculture (Llewellyn *et al.*, 2014; Schmidt *et al.*, 2017; Xiong *et al.*, 2019) and thus could explain the results seen in this study. Colonisation resistance of the gut microbiome is one of the main focus areas of antibiotic resistance research (Carlet, 2012; Kim, Covington and Pamer, 2017).

## 4.5. Conclusions

This chapter considered how a set of biological factors and the interaction between them can affect the sustainability of the social-ecological system. This study thus aimed to assess the impact of geographical location, habitat, and environmental conditions on mud crab gut microbiome diversity and abundance.

By comparing the relative abundance and bacterial diversity of crab guts from wild and pond cultivated crabs from both the east and west coasts of South India, habitat, location, crab body mass and carapace width, and water salinity were found not to induce changes in the gut microbiome. No statistically significant differences in gut bacterial composition were seen between the two coasts, suggesting that the discrepancy in engaging in mud crab farming most probably is rooted in socioeconomic factors. Meanwhile, the water temperature was shown to influence gut bacterial diversity, which tended to decrease with increasing water temperature. Human and animal pathogens made up less than 0.1% of the samples analysed. Thus, our findings suggest that current practices of crab farming result in healthy crabs and that geographical location should not impact farm success. Yet, in the context of climate change, further research is required to assess the effects of temperature on gut microbiomes, and their functions, and whether and how controlling temperature in aquaculture settings might help offset changes associated with variability in climate. However, it is important to note that the gut microbiome is only one factor out of many that can affect and induce changes in health status. These findings also indicate that in addition to overexploitation, increased temperature as a result of climate change could be another potential threat to wild *S. serrata* populations. Furthermore, India has developed a central hatchery for *S. serrata* seed to promote the uptake of mud crab aquaculture.

By considering social and ecological systems to be tightly linked as one unit, it allows exploration of how various interactions affect one or all of the components of the social-ecological system. For instance, the results of this study do not indicate that farmed crabs will be disadvantaged compared to their wild counterparts in terms of their gut microbiome composition. Simultaneously, however, that draws attention back to the importance of governance systems and socio-economic factors. Nevertheless, this study has also revealed the influence of related ecosystems in terms of climate change, which can negatively affect resource units, resource systems, socio-economic attributes of actors and focal action situations.

# Chapter five: Direct and indirect impacts of climate change on juveniles of the mud crab *Scylla serrata*

## 5.1. Introduction

Individual social-ecological systems are not isolated entities that are only affected by the events and choices within the system. They are constantly influenced by external factors such as changes in the political and economic situation on a local or global scale, demographic trends, advances in technology, climate patterns and pollution and flows between the systems. Climate change, caused by anthropogenic activities involving fossil fuel and agricultural emissions, arguably is currently one of the most important factors having a direct and indirect impact on social-ecological systems. Projections under different emission scenarios show that global land and water temperature has been rapidly increasing since the 1950s and will continue to increase (IPCC, 2014). These increases in global temperature are also projected to increase the occurrence of extreme weather events such as increased precipitation, leading to flooding, hurricanes, heatwaves, droughts and wildfires depending on the geographical location (IPCC, 2014). Thus, climate change in its varied forms poses various threats to the biological, physical and human systems across the globe causing the loss of livelihoods, reduced food security and water availability, loss of biodiversity, range shifts of terrestrial and aquatic species and many more challenges (IPCC, 2014).

Marine ecosystems are particularly vulnerable as climate change is projected to cause increases in ocean temperatures, and particularly in tropical regions, associated increases in precipitation, causing seawater freshening (Bates *et al.*, 2008, Balaguru *et al.*, 2016) and stratification, leading to declining seawater oxygen levels (Keeling *et al.*, 2010). The oceans are also projected to continue to absorb atmospheric $CO_2$ as a result of anthropogenic emissions, causing ocean acidification (Doney *et al.*, 2009; Pendleton *et al.*, 2016; Wu *et al.*, 2018). The direct climate pressures such as warming, freshening, hypoxia, and acidification can also instigate several other indirect changes in marine ecosystems, altering the composition of the microbial and phytoplankton community at the base of the marine food chain (Hallegraeff, 2010; Burge *et al.*, 2014; Godhe *et al.*, 2015). More frequent harmful algal blooms (HABs) of toxin-producing algae can in turn have negative effects on marine organisms higher up the marine food chain, including negative impacts on human health. High biomass HABs causing hypoxia are also linked to the above-mentioned climate pressures, particularly in coastal regions (Wells *et al.*, 2015). Climate change has expanded the biogeographical ranges and intensity of blooms of several toxic algae species (Okolodkov, 2005), e.g., ciguatoxin producing dinoflagellates *Gambierdiscus* (Rajeish *et al.*, 2016), saxitoxin producing dinoflagellates *Alexandrium minutum* (Valbi *et al.*, 2019) and domoic acid producing diatom *Pseudo-nitzschia* (Trainer *et al.*, 2020). At the same time, increased sea surface temperature (SST) is a favourable environmental factor for *Vibrio* spp. that prefer warm (>15$^{o}$C) environments, and are one of the most abundant aquatic bacteria groups, with some of the species, especially in high concentrations, pathogenic having negative impacts on other aquatic organisms and humans (Vezzulli *et al.*, 2015). *Vibrio*-related infections are increasing worldwide affecting both humans and aquatic animals. Reoccurring breakouts of seafood-borne illnesses caused by *Vibrio parahaemolyticus* in Peru and Alaska, where historically it has been rarely reported, and *Vibrio vulnificus* associated with oysters harvested from the Gulf of Mexico, indicate that climate anomalies such as heatwaves and El Niño induced expansion of geographical and seasonal ranges are favouring these species (Martinez-Urtaza *et al.*, 2010). Similarly, Continuous Plankton Recorder (CPR) survey data from over four decades in the North Sea showed a significant increase in *Vibrios*, including cholera inducing *V. cholera*, associated with zooplankton in years with increased SST (Vezzulli *et al.*, 2012). Mud crabs and other crab species, especially at their larval stages and in hatcheries, are affected by luminescent vibriosis causing reduced growth and mortality (Lavilla-Pitogo and de la Peña, 2004; Jithendran *et al.*, 2010; Poornima *et al.*, 2012). Some strains of *V. harveyi* have been found to cause mass mortalities in swimming crab *Portunus trituberculatus* (Zhang *et al.*, 2014) and blue swimming crab *Portunus pelagicus* (Talpur *et al.*, 2011) hatcheries, the latter case being associated with the gut microbiome, affecting healthy larvae, megalopae and juveniles. Mud crab juveniles, especially in aquaculture settings, are also susceptible to *Vibrio* caused bacterial shell disease, which, although not lethal itself, can cause perforations in the shell leading to secondary infections (Lavilla-Pitogo and de la Peña, 2004). *Vibrio* induced acute hepatopancreatic necrosis disease affecting farmed shrimps has caused a combined economic loss for China, Malaysia, Mexico, Thailand and Vietnam of US$44 billion from 2010 to 2016 (Tang and Bondad-Reantaso, 2019).

Estuaries, being the link between the land and ocean, are subjected to the same changes including increasing temperatures, water acidification, freshening (Scanes *et al.*, 2020) or in some areas rising salinity (Robins *et al.*, 2016). In addition, estuaries play an important role in the biochemical cycling of nutrients, in particular nitrogen (N) and phosphorus (P) from freshwater to marine systems, yet climate change is inducing structural changes leading to eutrophication, hypoxia, harmful algal blooms and higher abundance of pathogens (Tappin, 2002; Statham, 2012; Malham *et al.*, 2014). Thus, mud crabs that spend their early life stages in marine environments and their adult life in estuarine environments are inevitably subjected to these direct and indirect effects of climate change throughout their life span.

A growing body of literature is focusing on how these combined changes are affecting aquatic animals and what the long-term consequences will be for their fitness. For example, changes in salinity for stenohaline or less euryhaline decapod crustaceans can induce delayed development at early life stages (Anger, 2003). Ocean acidification is known to induce the lowering of calcium carbonate saturation states that has adverse effects on shell-forming aquatic organisms, influencing their growth rate and moulting frequency (Doney *et al.*, 2009; Whiteley, 2011; Kroeker *et al.*, 2013). However, warming, both as extreme weather events and as an ongoing trend, is causing the widest range of adverse effects on aquatic organisms, including crustaceans. A study on fiddler crabs showed that higher temperatures required increased use of energy reserves and also induced changes in crab behaviour (da Silva Vianna *et al.*, 2020). Increasing temperatures are also reported to have adverse effects on survival rates of American lobster larvae (Waller *et al.*, 2017), Florida stone crab larvae (Gravinese *et al.*, 2018) and barnacle *Amphibalanus improvises* larvae (Pansch *et al.*, 2012). At the same time, climate change enhances susceptibility to diseases in crustaceans as temperature is an important factor influencing physiological and immunological responses to pathogens (Shields, 2019). However, little is known how the aforementioned climate change parameters affect juvenile crustaceans. It has been shown that an increase in temperature causes an increase in oxygen consumption in ridgetail white prawn

(*Exopalaemon carinicauda*) juveniles (Zhang *et al.,* 2015) and in combination with different salinities in Pacific blue shrimp (*Litopenaeus stylirostri*s, now known as *Penaeus stylirostris*) (Spanopoulos-Hernández *et al.*, 2005). Elevated temperature has also been shown to compromise the growth and survival of the shrimp *Macrobrachium amazonicum* juveniles (Bastos *et al.*, 2018).

Marine fisheries production is already reflecting the changes induced by climate change, in particular, warming. By measuring the impact of historical warming on the maximum sustainable yield (MSY) of 235 populations of 124 species from 38 ecoregions, it was found that MSY has decreased by 4.1% from 1930 to 2010 (Free *et al.*, 2019). Some of the assessed populations responded negatively and some positively, yet overexploitation was recognised as a major cause for decreased resilience of marine fish populations to climate change. While this dataset did not show any indications of a pattern of geographical locations that will experience negative or positive consequences, projections by Cheung *et al.* (2017) suggest that tropical regions will suffer the most, while this will have a positive effect on fish productivity at the poles. Yet, climate change is not exclusively affecting marine fisheries alone; inland fisheries (Comte *et al.*, 2013) and aquaculture (Dabbadie *et al.*, 2018) are equally under threat. Therefore it is important to assess how these external factors will affect the species that are economically important for local communities and introduced as alternative species to less sustainable ones. Thus, this study aimed to assess the ecophysiological susceptibility of juvenile mud crabs to climate change parameters such as warming and/or freshening of coastal waters and the interaction of these with climate change parameter induced changes in the marine microbial community.

## 5.2. Materials and methods

### 5.2.1. Experimental design and setup

To assess the direct and indirect effects of climate change, a multivariate experimental design approach was used which included two different levels of seawater temperatures, two different levels of seawater salinities and exposure to microorganisms. The two seawater temperature levels resemble the mean temperature of seawater surface temperature (SST) in the region (+28 °C) and the projected +4 °C increase (+32 °C) under future climate change conditions. Juvenile mud crabs tolerate a wide salinity range, thus two salinity levels correspond to the optimum sea surface salinity (SSS) (30 PSU) and the lowest salinity in which the survival rate is not impacted (20 PSU). Mud crabs tolerate wide temperature and salinity ranges, which, however, depend on the life stage and geographical location, but the optimum temperature and salinity for juvenile mud crabs are between 25 °C and 30 °C and 15 and 35 PSU, respectively (Ruscoe *et al.*, 2004; Nurdiani and Zeng, 2007). Juvenile crabs were also exposed to the pathogenic bacteria *Vibrio parahaemolyticus* (10,000 cells/ml/day). *V. parahaemolyticus* is a common marine and estuarine pathogen that can be both harmful for the host (aquatic animals) (e.g., Deng *et al.*, 2020; Hong To *et al.*, 2020) and humans, causing acute gastroenteritis by consuming contaminated marine products (Su and Liu, 2007).

Juvenile crabs (crablets, 3.92 ± 1.98 g body mass, approximately 30 mm carapace width) were obtained from the mud crab hatchery of the Rajiv Gandhi Centre for Aquaculture in Tamil Nadu, India in January 2020. Crablets were acclimated to laboratory conditions at ambient temperature and salinity for at least three days before being exposed to the experimental conditions. Crablets were exposed to the four climate change treatments for 10 days with or without microorganism exposure: ‘control’ (28 $^{o}$C + 30 PSU), ‘warming’ (32 $^{o}$C + 30 PSU), ‘freshening’ (28 $^{o}$C + 20 PSU) or ‘warming + freshening’ (32 $^{o}$C + 20 PSU). To achieve the desired temperature of +32 $^{o}$C by day zero for the groups exposed to warming, the water temperature was increased by +1 $^{o}$C per day by using stick heaters during the acclimation period. Similarly, salinity was decreased by 3 PSU per day by adjusting seawater with filtered freshwater to achieve the necessary salinity for the groups exposed to freshening.

The total number of 256 crablets per microorganism exposure (no microorganisms or *Vibrio*) were randomly divided into four groups of 64 animals assigned to one of the climate change experimental regimes including control. These 64 individuals were then once again randomly distributed in four 15 L buckets filled with 8 L filtered (5 µm filter sock) and aerated seawater with pipe fragments to serve as a refuge to reduce cannibalism (Fig.5.1). Each bucket consequently contained 16 animals at a density of two animals per litre. Those four buckets of the same treatment were placed into larger tanks with water, which were heated with stick heaters to reach experimental temperature. Due to this approach, it was not possible to randomise treatments within larger tanks to eliminate the tank effect. Temperature and salinity were recorded twice a day and adjusted if needed. Crablets were fed once a day with chopped prawns *ad libitum* and any leftovers removed. Dead animals, if any, were removed daily.

At the end of the exposure period (day 10), crabs of each bucket containing 16 animals were randomly assigned to one of the three groups (Table 5.1.) Group one crablets were used for the determination of oxygen consumption. Group two crablets were snap frozen and for determination of levels of ATP, ADP, AMP, glucose and glycogen and thus cellular energy status. Group three crablets were snap frozen for to the quantification of bacterial concentration by real-time PCR. Unfortunately, the samples of the latter two groups were unavailable for analysis due to the impact of COVID-19 and thus no results are presented.

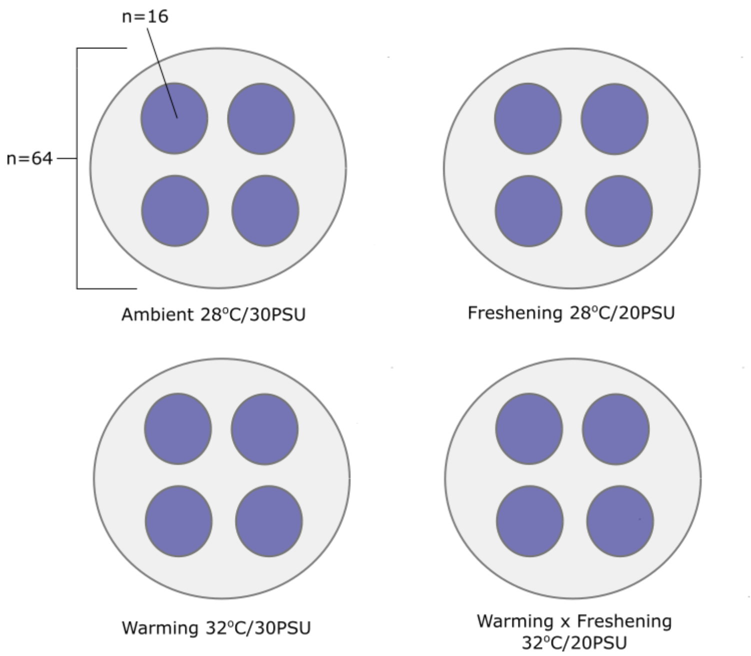


*Figure 5.1. Experimental set-up. Each larger tank was assigned to one treatment – ambient, freshening, warming or warming x freshening – and contained four 8L buckets with 16 animals*.

*Table 5.1. Sample sizes (n) for each analysis conducted on* Scylla serrata *after 10 d exposure to different simulated climate change conditions and microorganisms.*

| | | Toxicity * | Oxidative metabolism | Cellular energy status * |
|---|---|---|---|---|
| Microorganism exposure | Climate change | *Vibrio* uptake by qPCR | $O_2$ uptake | ATP, ADP, AMP, AEC, TAN, Glucose, Glycogen |
| No microorganisms | Ambient | 8 | 16 | 16 |
| | Freshening | 7 | 16 | 16 |
| | Warming | 3 | 12 | 12 |
| | Warming + Freshening | 7 | 16 | 16 |
| *Vibrio* | Ambient | 8 | 16 | 16 |
| | Freshening | 5 | 8 | 8 |
| | Warming | 4 | 11 | 8 |
| | Warming + Freshening | 4 | 16 | 16 |
| **Total sample size** | | **46** | **111** | **108** |

*Samples for determining *Vibrio* uptake and cellular energy status were processed but require further analyses that were not possible at the time this thesis was written due to the COVID-19 pandemic.

### 5.2.2. Determination of metabolic rates

Standard oxygen uptake ($MO_2$) after 10 days of exposure period was determined using closed chamber respirometry. Respirometry chambers (volume = 245 mL) containing a magnetic flea and a plastic mesh to prevent contact between the crablet and the magnetic flea, were filled with aerated and clean (filtered through a 0.22 µm filter) seawater at the respective experimental temperature and salinity. A crablet was added to each chamber and sealed while submerged in the water to prevent air bubbles. Before placing the chambers onto magnetic stirrers (Remi Laboratory Instruments, Mumbai, India) for preventing oxygen stratification with the chamber and ensuring adequate mixing, they were loosely covered with aluminium foil to minimise the disturbance to the animal. To establish resting $MO_2$, crablets were allowed to settle in the chambers for 40 minutes. Planar optode spots (diameter 0.5 cm; PreSens Precision Sensing GmbH, Regensburg, Germany) were glued to the inside of each chamber to allow oxygen levels to be measured. Oxygen levels in the chambers were measured every 5 min for a period of 1 h using a Fibox 4 oxygen meter (PreSens Precision Sensing GmbH). The decline in $pO_2$ over the measurement period was linear and was not allowed to fall to hypoxic levels. Background respiration was taken into account by running a series of blanks, and the average value across them was subtracted from the original $MO_2$ value. $MO_2$ was expressed as µmol $O_2$ h-1.g-1. After completing the measurements of $MO_2$, crablets were removed from the chambers and weighed. Crablet volume was also obtained by displacement.

### 5.2.3. Data analysis

Firstly outliers were detected based on the inter-quartile range rule multipliers 1.5 and 3.0 and eleven samples were identified as outliers, thus excluded from further analyses. Data did not meet assumptions for homogeneity of variances (Levene's test, $p>0.05$), yet was normally distributed according to Kolomogorov-Smirnov ($p>0.05$), but not according to Shapiro-Wilk ($p=0.004$). A two-way analysis of covariance (ANCOVA) was used to investigate the effect of climate change and microorganism exposure on oxygen consumption with crab body mass as a covariate as it was found to be statistically significant. In the preliminary analysis, the term 'tank' as a random factor was found not to have a significant effect on the oxygen consumption, thus was excluded from further analyses. Although two way ANOVA is a parametric test, it is regarded as a robust and powerful test that can be used for non-normally distributed data (Underwood, 1997). Besides, the result of Levene's test, run at the same time as two-way ANCOVA, showed that data met assumptions for homogeneity of variances ($p>0.05$). Post-hoc Bonferroni tests adjusted for covariates were conducted to identify differences between groups. One-way ANOVA was used to test whether survival rates were impacted by climate change or microorganism exposure. Two-way ANOVA was used to test whether exposure to microorganisms has a significant effect on oxygen consumption if the crab body mass is not seen as an essential covariate. All analyses were conducted in SPSS v.25.

## 5.3. Results

### 5.3.1. Survival rates

Survival rates were greater than 85% in most treatment groups, and the lowest survival rate was 66.66% in the group exposed to *V. parahaemolyticus* and warming (Table 5.2.). There were no statistically significant differences in survival rates between groups ($p>0.05$). One replicate (a tank of 16 crabs) from the no microorganism exposure group and two replicates from the *Vibrio* exposure group were lost due to technical issues at the start of the exposure and thus were excluded from the total number of crabs used in the experiment.

*Table 5.2. Survival rates and average body mass (±SD) for* Scylla serrata *juveniles after 10 d exposure to different simulated climate change conditions and microorganisms.*

| Microorganism exposure | Climate change | % Survival | Body mass (g) |
|---|---|---|---|
| No microorganisms | Ambient | 95.31 | 5.5 ± 1.05 |
| | Freshening | 90.62 | 7.09 ± 1.94 |
| | Warming | 79.16 | 3.92 ± 0.91 |
| | Warming + Freshening | 89.06 | 3.21 ± 0.93 |
| *Vibrio* | Ambient | 93.75 | 2.99 ± 0.98 |
| | Freshening | 87.50 | 2.11 ± 0.4 |
| | Warming | 66.66 | 2.71 ± 1.53 |
| | Warming + Freshening | 71.87 | 2.55 ± 0.61 |

### 5.3.2. Metabolic rates

The two-way ANCOVA removing/accounting for crab body mass showed that simulated climate change had a significant effect (p=0.000) on the oxygen consumption rate, while the combination of microorganism exposure together with climate change did not have any effect (p>0.05) (Table 5.3.). Microorganism exposure alone was not statistically significant if the p-value of the significance level α is considered to be 0.05. However, p-value=0.068 indicates a trend thus is recognised as significant. Crab body mass as a covariate had a statistically significant effect on oxygen consumption. Pairwise comparisons, Bonferroni post-hoc tests, based on means and adjusted for crab body mass, showed a statistically significant difference between ambient and freshening groups (p=0.001), between freshening and warming (p=0.024), and between freshening and warming + freshening (p=0.000). Yet, there were no statistically significant differences between ambient and warming and between ambient and warming + freshening groups (p>0.05). However, the mean oxygen consumption of juvenile mud crabs not adjusted for crab body mass showed increased oxygen consumption in all simulated climate change groups exposed to *Vibrio* compared to juvenile crabs not exposed to pathogenic bacteria (Figure 5.2.).

*Table 5.3. Results of parametric two-way ANCOVA with crab body mass as a covariate of the effects of simulated climate change conditions and microorganism exposure on oxygen consumption (n=100).*

| Test | Body mass | Climate change | Microorganism exposure | Climate change + Microorganism exposure |
|---|---|---|---|---|
| Two-way ANCOVA | **p=0.000** **$F_{(1,91)}$= 112.380** | **p=0.000** **$F_{(3,91)}$= 7.984** | **p=0.068** **$F_{(1,91)}$= 3.409** | p=0.966 $F_{(3,91)}$= 3.409 |

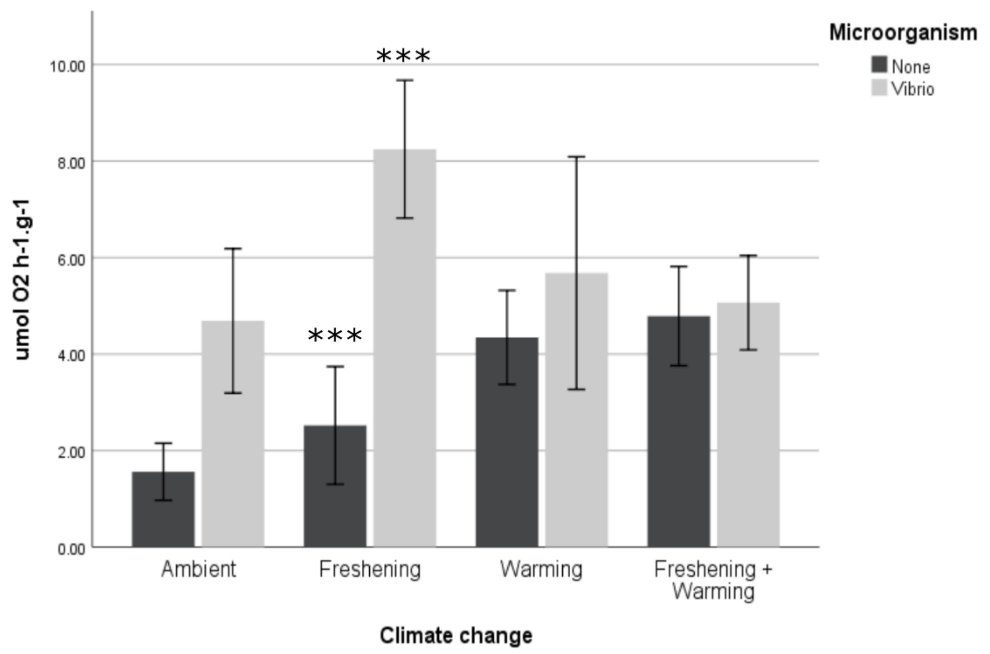


*Figure 5.2. The mean oxygen consumption of juvenile mud crabs ± SD (confidence interval ±95%) in simulated climate change conditions and microorganism exposure. Three asterisks indicate p≤0.001 between ambient and simulated climate change groups*

## 5.4. Discussion

Considering projected climate change under different emission scenarios (IPCC, 2014), it is evident that climate patterns are, and will be an important factor altering resource units and consequently the whole social-ecological system. Aquatic animals already are forced to adapt to changing climate, yet simultaneously are being exposed to sudden extreme weather events such as marine heatwaves, causing range shifts of species and mass mortalities

(Frölicher and Laufkötter, 2018; Cheung and Frölicher, 2020) that consequently adversely affect the livelihoods of local communities that depend on fisheries and aquaculture. Besides sea level rise along with more frequent and intense storms and modified wave patterns will impact overall coastal evolution influencing habitats and infrastructure (Church *et al.*, 2013; Ranasinghe, 2020). This study aimed to assess how the direct climate change outcomes (warming and freshening) and indirectly induced abundance of pathogenic bacteria will affect the physiology of mud crab *Scylla serrata* juveniles. It is especially important to understand the impacts on early life stages, as juveniles generally are more susceptible to any changes. However, there are limited data on the climate change effects on crustacean juveniles. The studies available mainly focus on survival rates and development. Studies have shown that mud crab larvae are significantly affected by the interaction between temperature and salinity and low survival rate and low or prolonged metamorphosis to the megalopa stage have been observed if the salinity and temperature are both low or high (<15PSU and >35 PSU, and <20 $^{o}$C and >35$^{o}$C, respectively) (Hamasaki, 2003; Baylon, 2010). Simulated climate change experiments with Florida stone crab larvae showed that the projected +4 $^{o}$C increase in temperature significantly decreased their survival rate (Gravinese *et al.*, 2018). Yet, with regards to mud crabs, the tolerance to wider temperature and salinity range increases with growth (Baylon, 2010) and the weight-specific growth rate of *S. serrata* juveniles were shown to be more influenced by the temperature rather than salinity (Ruscoe *et al.*, 2004). In this study, no significant mortality was observed as expected; temperature and salinity of simulated climate change were chosen to potentially induce physiological stress, but not cause mass mortality.

The results of this study showed that simulated climate change conditions (especially freshening) significantly increased oxygen uptake in juvenile mud crabs. Similar results on juvenile *S. serrata* were obtained by Chen and Chia (1996), showing low salinity and elevated temperature to increase oxygen uptake and also proposing that energy expenditure of juvenile mud crabs is lower at 25 PSU and 30 PSU compared to 15 PSU and 20 PSU. It has also been found that decreased salinity (4 PSU) induced high activity of $Na^{+}/K^{+}$-ATPase in posterior gills of juvenile *S. serrata* (Romano *et al.*, 2014), which is an important osmoregulatory response of euryhaline estuarine crustaceans when exposed to low salinities (Lucu and Towle, 2003). This means that ions are being actively pumped from water into the haemolymph. Adult *Scylla olivacea* exhibited an identical response when exposed to salinities at 5, 10 and 15 PSU (Boonsanit and Pairohakul, 2021), indicating that osmoregulation is consistent at all development stages. Another study *on S. oliveacea* showed that exposure of adult mud crabs to freshwater (0 PSU) rapidly increased oxygen consumption, which then gradually declined after 12 hours and became stable after 4 days (Rahi *et al.*, 2020). Thus it is evident that freshening induces stress in animals, yet cell processes of mud crabs are well adapted to varying salinities and have various osmoregulatory mechanisms to reduce any damage. Yet, hypersalinity (35 PSU) is more likely to cause severe oxidative stress than freshening (Paital and Chainy, 2010), which should be considered in aquaculture settings. The results of this study, however, showed a statistically significant increase in oxygen consumption in crabs exposed to freshening and as tropical regions are expected to experience increased monsoon rainfalls (Bates *et al.*, 2008), it is essential to have a deeper investigation.

Studies on different salinity regimes have shown that increased oxygen uptake is connected to increased activity of $Na^+/K^+$-ATPase and indicates higher energy consumption (Rahi *et al.*, 2020; Boonsanit and Pairohakul, 2021). The majority of studies investigating metabolic rates and energy consumption of crustaceans in addition to determining oxygen consumption assess ammonia excretion (Chen and Chia, 1996; Pillai and Diwan, 2002; Shock *et al.*, 2009; da Silva Vianna *et al.*, 2020), yet do not exhaustively investigate cellular metabolic processes. Thus, one of the original objectives of this study was to analyse the cellular energy status by identifying levels of ATP, ADP, AMP, glucose and glycogen that would help to understand the cellular metabolic process underpinning the physiological response of these crabs in detail. Unfortunately, these samples are unavailable for analysis due to the impact of COVID-19. While the effects of salinity on *Scylla* spp. have been widely studied, there is limited data on how warming affects mud crab physiology at any life stage. Crustaceans are ectothermic, which means that they cannot control their internal temperature and it depends on the environment, thus their energy metabolism consequently is directly influenced by any changes in environmental temperature (Lagerspetz and Vainio, 2006).

Studies on glucose and glycogen contents of crustaceans exposed to warming have shown varied results. A study on gammarids *Gammarus pulex* reported a slight decrease in glycogen content at 27°C of southern populations, indicating that glycogen is being broken down to glucose to be used for energy, while northern populations responded similarly when temperatures were below 15°C (Foucreau *et al.*, 2014). Meanwhile, aeglids, freshwater crustaceans, showed higher glycogen levels and lower protein levels at a higher temperature compared to ambient conditions, (Cogo *et al.*, 2017), suggesting that different crustacean species use different energy sources when exposed to environmental stress. Thus, it is not possible to fully predict the outcome of the results of metabolite levels in mud crabs in simulated climate change conditions.

It is known that both high (40°C) and low (15°C) temperatures induce oxidative stress that leads to weakened cellular respiratory functions in *S. serrata* (Paital and Chainy, 2014). A study on mitochondrial metabolite levels of *S. paramamoisan* populations from south and north of China also showed that northern populations adapt better to seasonal temperature variations (Liu *et al.*, 2013). In addition, habitat can also define physiological responses. Fiddler crabs from unvegetated areas increased their oxygen consumption consequently adjusting their metabolic rate as a response to a higher temperature, while crabs from vegetated areas that are used to having a refuge were more vulnerable to warming at laboratory conditions (da Silva Vianna *et al.*, 2020). These findings underline the importance of research on temperature effects on different species in different geographical locations. Warming also affects crustacean behaviour – increases time spent in burrows and decreases their activity and feeding time (Lozán, 2000; Cogo *et al.*, 2017; da Silva Vianna *et al.*, 2020). Although behavioural observation and quantification of feed leftovers were not part of this study, crablets in warming and warming + freshening left more uneaten feed and were seemingly less active. However, mud crabs are mainly nocturnal, thus a different experimental design would be beneficial in future to assess the impact of increased temperature on their behaviour.

Not every aquatic organism will be negatively affected by projected future climate change conditions. Some, such as bacteria and algae thrive at increased temperatures and different climate change induced salinities. However, those thriving are often pathogenic bacteria (Burge *et al.*, 2014) and toxin-producing algae of harmful algal blooms (Wells *et al.*, 2015), adding yet another pressure on animals and humans already exposed directly to warming and freshening. The role of climate change in emerging and re-emerging bacterial diseases affecting humans has been widely acknowledged (El-Sayed and Kamel, 2020), yet less attention has been brought to how more abundant pathogenic bacteria especially in tropical regions will affect the physiology and health status of aquatic animals. Although the calculated measure of probability was higher than the conventional, yet the arbitrary level of significance of 0.05 (Di Leo and Sardanelli, 2020), there is a noticeable trend of increased metabolic rates in animals exposed to *V. parahaemolyticus*, which requires further investigation. In addition, crabs exposed to *Vibrio* were slightly smaller compared to the group not exposed to microorganisms despite random selection. Random selection has its limitations as to avoid cannibalism similar size crabs had to be put together in the same tank.

The highest oxygen uptake indicating potential oxidative stress and high energy consumption was observed in crabs exposed to freshening and V. *parahaemolyticus,* yet interestingly metabolic rates were not significantly affected by the presence of pathogenic bacteria in animals exposed to warming and warming + freshening compared to the same simulated climate change conditions not exposed to microorganisms. The optimum growth conditions of *V. parahaemolyticus* are 20–25 PSU and 30–35 °C (Jones, 2014), thus the simulated climate change conditions should not have affected bacterial colonies. However, the interaction between environmental conditions and time of exposure has been reported to impact the scale and intensity of infections in blue crabs, *Callinectes sapidus* (Sullivan and Neigel, 2018). It is possible that *V. parahaemolyticus* were not taken up effectively by the juveniles due to thermal and salinity stress, therefore quantification of bacteria by real-time PCR was intended. Previously it has been demonstrated that *V. parahaemolyticus* amplified significant negative effects caused by warming and freshening on metabolic and immunobiological status of mussels, *Perna viridis*, simultaneously increasing toxin-pathogen load that could adversely affect seafood consumers (Turner *et al.*, 2016). Although mud crab juveniles are not filter feeders like mussels, by being exposed to free-living bacteria and potentially feeding on infected molluscs and fish, pathogenic bacteria could compromise their physiological health. Further research is also necessary to assess the toxin-pathogen load in adult mud crabs concerning food safety.

## 5.5. Conclusions

In general, crab species from the *Scylla* genus and, in particular, *Scylla serrata*, have been widely studied due to their commercial importance. However, there are some aspects of their biology that are less studied. The effects of direct and indirect climate change parameters on the physiology of mud crabs and crustaceans, in general, have not gained the desired attention despite the potential adverse influence of climate change on both natural and human systems they are a part of. This study showed that the exposure of juvenile mud crabs to warming, freshening and warming + freshening induced an increase in metabolic rate which indicates higher energy levels are needed to regulate physiological processes that maintain homeostasis. Freshening, in particular, was a statistically significant factor, and already increasing monsoon rainfalls could cause oxidative stress and compromise the immunobiological status of juvenile mud crabs and make them potentially more susceptible to disease. Exposure to pathogenic marine bacteria *V. parahaemolyticus* revealed a trend of increased oxygen consumption in juvenile crabs, however, further research is required to investigate immunological responses to *V. parahaemolyticus.* Survival rates were not significantly influenced by simulated climate change conditions or microorganism exposure, yet the study was relatively short (10 days), therefore studies exposing juvenile crabs to these conditions for longer and assessing their transformation to the sub-adults are also necessary. In addition, further studies investigating the effects of different salinity regimes are also required.

It is of great importance to understand the impacts of climate change on mud crabs and other tropical crustacean fisheries and aquaculture as they are an essential livelihood resource for many people. As an important source of protein, they also play a significant role in food security. Besides inhabiting estuaries and mangroves juvenile and adult mud crabs are a part of a complex and rich natural ecosystem playing their part in maintaining its balance. Thus such studies can inform local communities and policymakers focusing either on mangrove biodiversity conservation or empowering local communities. Understanding the impacts of temperature increase and salinity changes can also ensure timely adaptation, for instance, temperature and salinity regulation in aquaculture farms.

# Chapter six: the synthesis

## 6.1. Introduction

Coastal zones, particularly in tropical countries, are complex, dynamic and resource rich areas that, being at the interface between land and water, provide essential livelihoods for communities relying on the ecosystem services provided by the coastal areas (Cinner and Bodin, 2010; Neumann *et al.*, 2015; Jayanti *et al.*, 2018). Fishing is often one of the most common income generating and subsistence providing activities for such coastal communities (Campbell *et al.*, 2006; Allison and Ellis, 2001). Yet, coastal areas are constantly affected by biophysical changes, land use changes, tourism, population growth, pollution and many other factors (Campbell *et al.*, 2006). Thus, ongoing pressures caused by climate change and population growth such as depleted fish stocks have significant negative effects on these already vulnerable communities (Allison *et al.*, 2005; Béné, 2009). Consequently, local communities are required to diversify their livelihoods (Barrett *et al.*, 2001), yet some activities such as intensive aquaculture, e.g., of shrimp, can be environmentally, socially and economically unsustainable (Páez-Osuna, 2001; Blythe *et al.*, 2015).

This thesis considers the potential of the mud crab *Scylla serrata* as an environmentally (biologically), economically and socially sustainable livelihood resource for local communities in southwest India. This species was chosen as a prime candidate for such investigation due to its high economic value and suitability as a sustainable farming species (Keenan, 1999; Shelley and Lovatelli, 2011). At the same time, nutritional value and food security are other important factors that have to be taken into account as India's population is projected to increase to 1.6 billion by 2050 (United Nations, 2015), yet The Global Nutrition

Report in 2018 (Development Initiatives, 2018) reported that 46.6 million children in India are stunted (below average height) and 25.5 million children are wasted (below average weight).

Fisheries and aquaculture encompass social and natural systems and are inherently embedded in complex social-ecological systems (Partelow and Boda, 2015). Therefore this thesis has taken an interdisciplinary approach to identify the main barriers and drivers of this social-ecological system. The key objectives of this work were to:

1. Determine the perceptions of fisher communities of the mud crab as a sustainable livelihood resource and identify the main socio-economic challenges for undertaking small-scale mud crab farming in southwest India.
2. Evaluate the long term feasibility of already implemented small-scale mud crab farms in southeast India and identify drivers and limitations to small-scale mud crab aquaculture.
3. Identify how geographical location, habitat and environmental factors influence the composition of the mud crab gut microbiome and how that affects crab health status.
4. Assess how direct and indirect climate change parameters affect the physiological responses of juvenile mud crabs.

This chapter links the findings of each experimental chapter with the help of systems thinking and the social-ecological systems (SES) framework. It reveals the interconnections and dependencies between actors (fishers/crab farmers), resource systems (fisheries and/or aquaculture), resource units (mud crabs) and governance systems, thus identifying whether the mud crab *Scylla serrata* can be perceived as an environmentally, socially and economically sustainable source of livelihoods for fisher communities in southwest India, in particular, in the state of Karnataka. Furthermore, the drivers and barriers to sustainable mud crab harvesting are identified and analysed.

## 6.2. Linking social and ecological systems

This thesis consists of four standalone research studies with four different objectives. Yet, each of these studies investigates components that are a part of a complex and dynamic social-ecological system. Thus, by looking at the results holistically, it is possible to identify the flows and dynamics between those components. Several frameworks can be used to analyse social-ecological systems, each with its own purpose and scope of application (Binder *et al.*, 2013). The social-ecological system (SES) framework established by Elinor Ostrom (2007; 2009), based on systems thinking, is an analysis-oriented framework that considers feedback loops between the elements of the system, accounting for the system dynamics on all hierarchical levels (Binder *et al.*, 2013). It also allows the integration of data from diverse disciplines (Leslie *et al.*, 2015) as shown in this thesis, such as socio-economics (chapter two and chapter three), microbiology (chapter four) and ecophysiology (chapter five). An additional analytical framework – sustainable livelihood approach (SLA) - was chosen to be applied in chapter two as it focuses on livelihoods, considers vulnerability context which is mainly environmental and identifies capital assets. The SLA thus contribute to understanding local fisher communities and their standpoint. However, it only considers the local scale and cannot be translated to a bigger scale and SLA does not conceptualize social or ecological system dynamics (Binder *et al.*, 2013), therefore it was not considered as the most appropriate framework for analysing overall findings.

The SES framework as described in chapter one consists of 8 main components and each of those components has various second and lower-tier attributes (Table 1.2.). Not all of the attributes are relevant to the particular social-ecological system in focus or have the same level of importance. For this social-ecological system, it was possible to identify 47 second-tier and 17 third-tier variables (Fig. 6.1.) from the studies conducted. Out of these 64 attributes, 26 were identified as essential components that determine the sustainability of this social-ecological system (Fig.6.2).

The next sections discuss in detail the components of the social-ecological system in question, describe the feedbacks and dependencies between them and identify which components facilitate and which limit this SES to be sustainable and consider leverage points that could induce shifts to achieve sustainability of this social-ecological system.

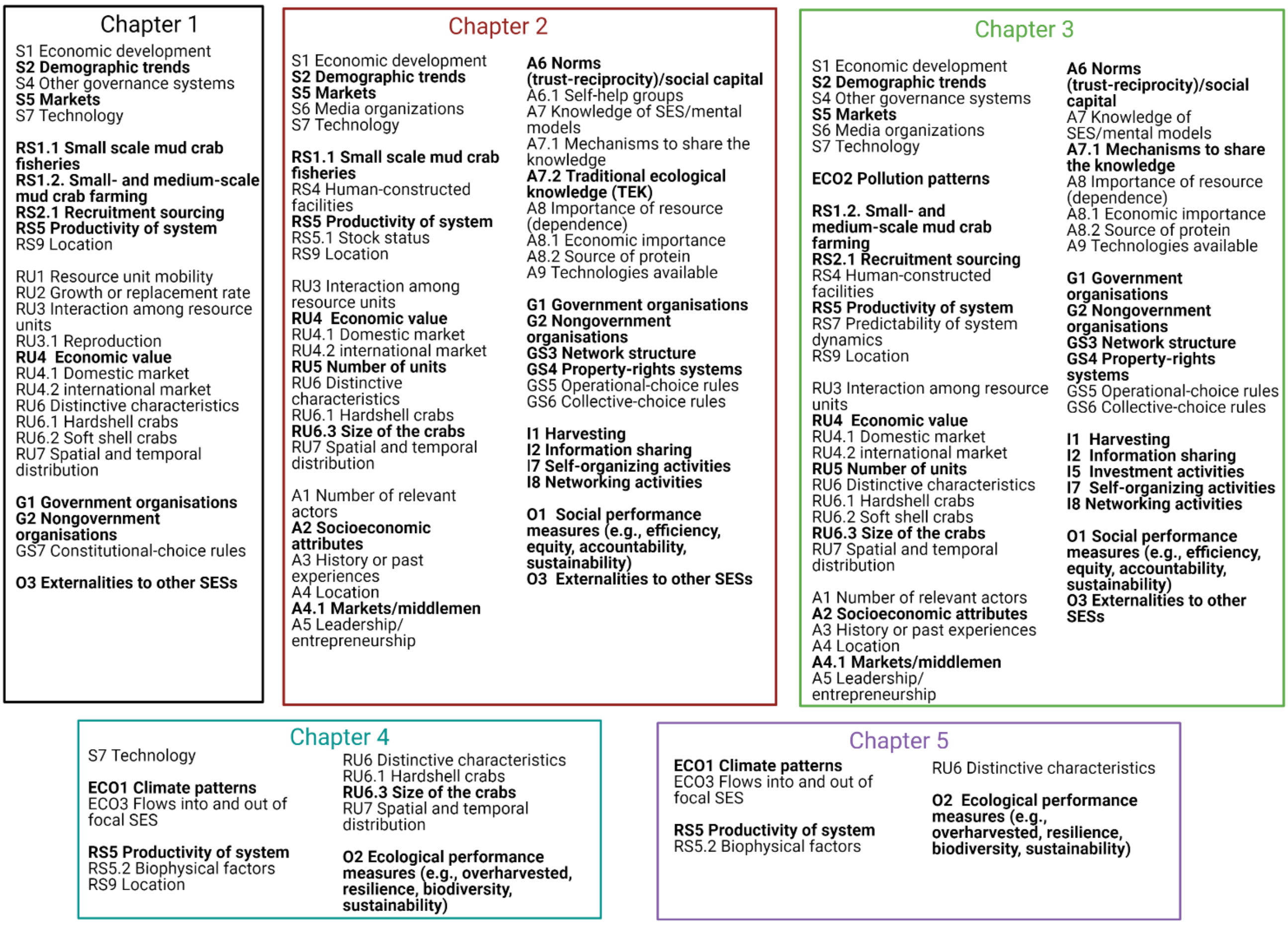


*Figure 6.1. Modified second-and third-tier variables of a social-ecological system framework for small-scale mud crab fisheries and aquaculture in South India identified and discussed in each chapter. Tiers adapted from McGinnis and Ostrom (2014) and Basurto et al. (2013). Components in **bold** have been identified as important variables determining the sustainability of this SES and are further discussed in this synthesis chapter.*

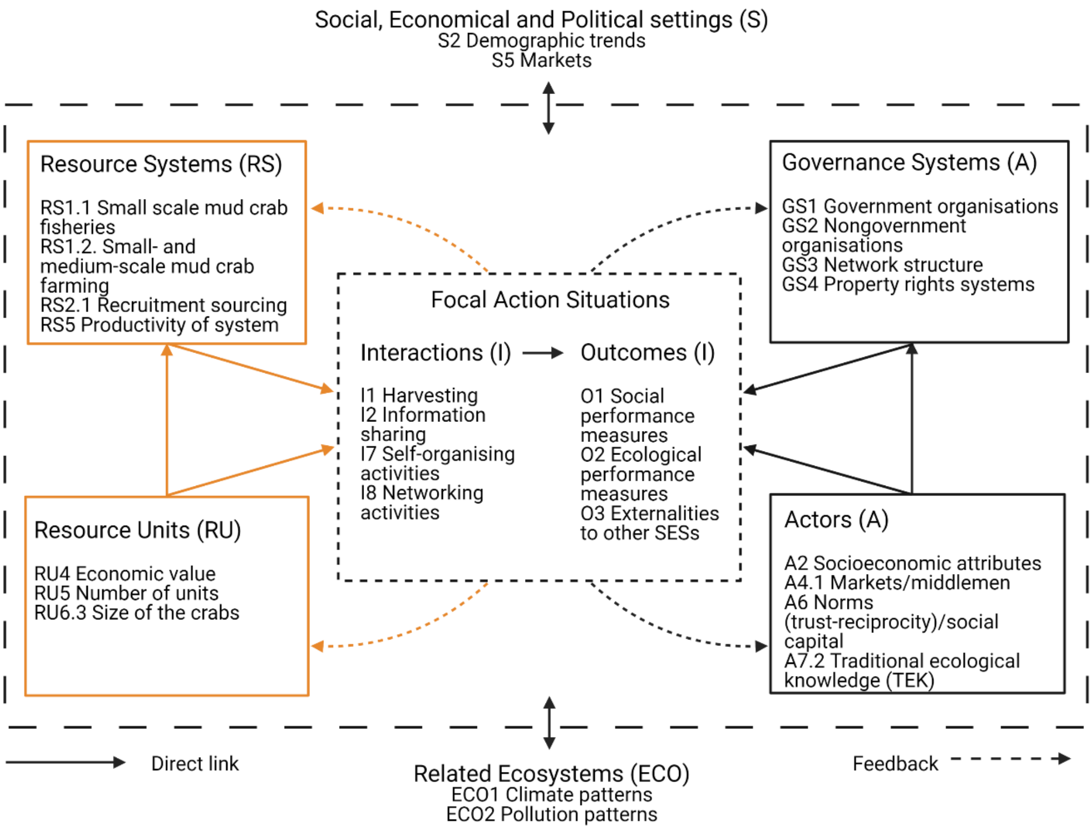


*Figure 6.2. Modified social-ecological system (SES) framework (adapted from McGinnis and Ostrom, 2014) with 26 essential attributes of this SES. The dashed line around the exterior indicates that the focal SES is a whole independent system, yet is influenced by external factors such as social, economic and political settings and related ecosystems. Solid boxes indicate first-tier components that contain second- and lower-tier variables. Focal action situations in the middle denote where all the action takes place as inputs are transformed by the actions of variables into outcomes. The dotted lines indicate feedbacks from action situations to first-tier components. Figure created with BioRender.com.*

### 6.2.1. Resource systems and resource units

This social-ecological system as mentioned earlier includes two resource systems that could exist as two independent systems, yet, as shown in chapter three, crab farmers rely heavily on crabs caught from estuaries. Thus, small-scale mud crab fisheries and crab farming are perceived as sub-systems of this SES.

Fisheries at their core are common-pool resources (CPR) and can be characterised by low excludability (available to almost all users) and high subtractability (resources consumed by one user subtract from what is available to other users) (Hinkel *et al.*, 2015). Resource systems from a CPR perspective are seen as common stocks and resource units that are harvested by the appropriators (actors), and are perceived as flows, but not as subject to joint appropriation (Ostrom, 1990). The results of chapter two showed that small-scale mud crab fisheries were not perceived as an economically sustainable source of livelihood by local communities. The high economic value on its own was not enough compared to irregular catches and the unpredictable size of the crabs (RU6.3) that determine the selling price (Fig.6.3). However, the economic value (RU4) can be perceived as a reinforcing feedback loop (Meadows, 2008) as it is the main reason why members of local communities are increasingly involved in crab fishing or crab farming. The economic value in turn is controlled by the market demand which is discussed in further sections. Unfortunately, the prospect of relatively high income from mud crabs has created significant competition leading to possibly full exploitation of mud crabs (decrease in the number of units RU5) and potentially 'the tragedy of the commons' – a concept that brought the attention of common-pool resources (Hardin, 1968).

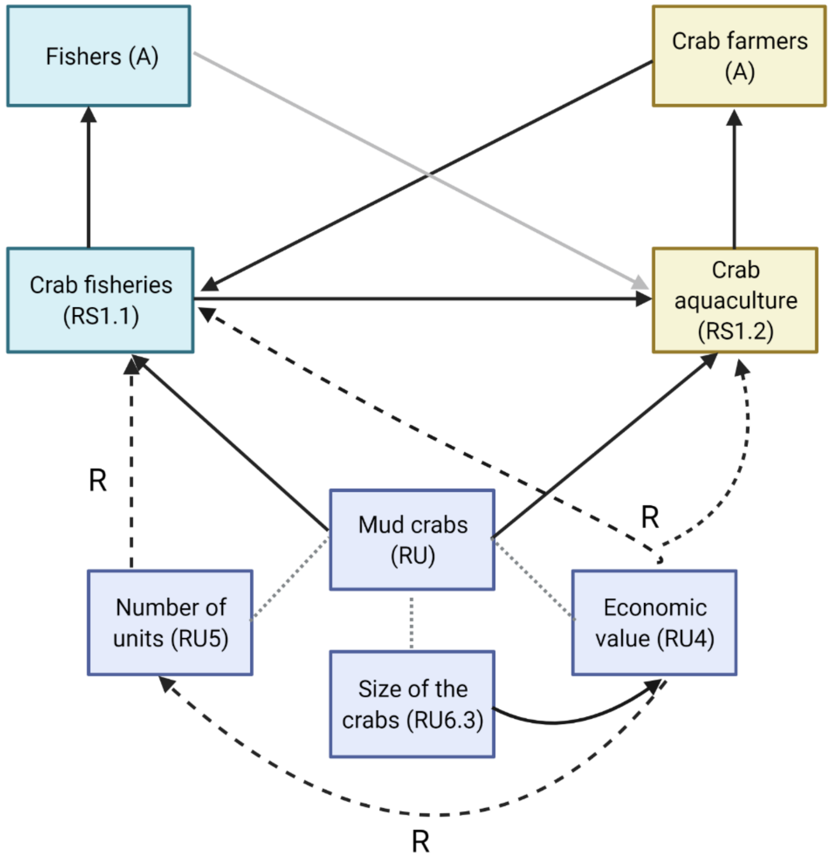


*Figure 6.3. Flows and attributes of two SES subsystems - crab fisheries (RS1.1) and crab aquaculture (RS1.2). Grey dotted lines indicate attributes of Resource Units. Black arrows indicate the links and grey arrows indicate a potential link. Black dashed lines indicate reinforcing loops that can either induce growth or destruction (Meadows, 2008). Created with BioRender.com*

It is difficult to fully assess the productivity of this resource system (RS5) as data on stock assessments of inland and coastal fisheries in tropical regions, including mud crabs, are scarce. The available data on catch per unit effort (CPUE) of mud crabs were discussed in chapter two and suggested that CPUE is not decreasing rapidly (Walton *et al.*, 2006; Lebata *et al.*, 2007; Sen and Homechaudhuri, 2017). The perception of local fishers, however, indicates that the number of resource units could be negatively affected. However, the decrease in catch per fisher could simply reflect the increase in the number of fishers thus resulting in fewer crabs harvested per person, while maintaining stable populations of *S. serrata*. Nevertheless, fishers' local ecological knowledge should be acknowledged as an important complementary tool in monitoring the catches (Martins *et al.*, 2018) as data poor does not necessarily mean information poor. Increased fishing effort in a particular area can affect the average size of the crabs caught. A study in Malaysia showed that 80% of mud crabs caught were immature (Kosuge, 2001), thus significantly influencing potential reproduction (RU3.1) and replacement of resource units. The size also affects the selling price and the sensitivity analysis conducted in chapter three indicated a significant decrease in net present value (NPV) if the average weight of the crab is 300g, especially affecting small-scale fishers. Yet, as seen in Figure 6.3 and mentioned earlier, crab aquaculture (RS1.2) is tightly linked with crab fisheries (RS1.1) and shares the same resource units. One working mud crab *S. serrata* hatchery cannot meet the demand and as chapter three reported, favour mainly large-scale farms. Thus, this is the **first leverage point** or a point of intervention identified that could alter the behaviour of this social-ecological system (Meadows, 2008). The insufficient supply (RS2.1) to crab farmers could adversely affect wild mud crab populations and consequently fisher communities. Yet, on the other hand, an increased supply of commercial *S. serrata* seeds for mud crab farmers which, as the results of chapter four suggest, should not compromise crab health status, and could relieve pressure on wild populations and fisher communities. Such a scenario nevertheless holds new governing challenges to ensure equal access.

### 6.2.2. Social capital, networking and self-organising activities

The role of governance systems is to set rules for actors using resource systems (McGinnis and Ostrom, 2014) and governance rules and approach is central to the SES framework (Ostrom, 2007, 2009; McGinnis and Ostrom, 2014). In the case of common-pool resources, governing is the main challenge as each individual is concerned about their own livelihoods (Berkes and Folke, 1998). Hardin (1968) proposed that CPRs should be governed, almost exclusively, by the government. As such suggestion questions the whole idea of free common resources, more focus has been drawn to the self-organising and self-governing of CPRs (Ostrom, 1990).

By identifying governmental and non-governmental organisations and the links between them, it is possible to create a formal network structure (Fig. 6.4). Small-scale coastal and inland fisheries in India are not governed or regulated by any governmental or nongovernmental entity, thus there are no monitoring and sanctioning rules (GS8). Meanwhile, saline and brackish water aquaculture in coastal areas, including crab farms, have to be registered with the Coastal Aquaculture Authority (CAA) and are regulated by the Coastal Aquaculture Authority Act 2005. According to the CAA Act 2005 any culture under controlled conditions, including traditional aquaculture, must be registered. However, it is not clarified what classifies as traditional aquaculture and whether farming in *gazani* watersheds, described in chapter two or common waters, such as described in chapter three, would fall under this category and should be registered. The Central Institute of Brackishwater Aquaculture carries out research on brackish water farming methods, diseases and provides training for crab farmers (CIBA, 2020). However, the training courses usually do not take place locally and also have an attendance fee, thus members of fishing communities such as those interviewed in chapter two, are often unable to access these courses to learn farming techniques.

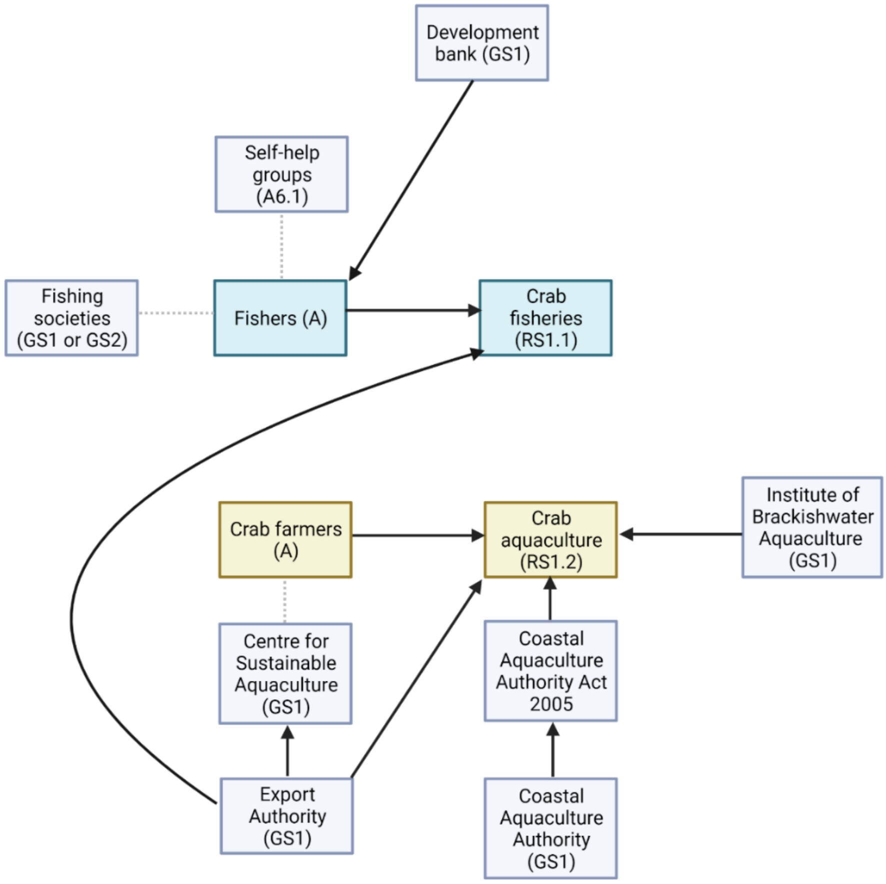


*Figure 6.4. Network structure including crab fisheries, crab aquaculture, government and non-government organisations, and social capital. Grey dotted lines indicate social capital and organisations offering support, identified in chapter two and chapter three. Full names of organisations: Development Bank - National Bank for Agriculture and Rural Development (NABARD), Institute of Brackishwater Aquaculture – Central Institute of Brackishwater Aquaculture (under Indian Council of Agricultural Research) (ICAR – CIBA), Export Authority – Marine Products Export Development Authority (MPEDA), Centre for Sustainable Aquaculture – National Centre for Sustainable Aquaculture (NacSA). GS1 indicates government organisations, GS2 - nongovernment organisations, A means actors and RS means resource systems. Created with BioRender.com.*

The scarcity of formal organisations underlines the importance of social networks and social capital, especially for fisher communities. Social networks between actors are part of the social capital an individual or a group can possess together with trust, norms and reciprocity (A6) (Woolcock, 1998). Social capital is necessary for collective action to achieve the greater good for the community as a whole (Adger, 2006) by self-organisation and community based natural resource management (Pretty and Ward, 2001). Chapter two identified two components of social networks in fisher communities – self-help groups (A6.1) and formal fishing societies (regulated by the local administrative authority GS1 or nongovernmental GS2). Self-help groups (SHGs) are shown to decrease the indebtedness of coastal fishers compared to those not being a part of an SHG (Vipinkumar *et al.*, 2014). Similarly, chapter 2 showed that SHG members had higher financial capital compared to other respondents. Chapter three showed that crab farmers in Andhra Pradesh have access to local branches of the National Centre for Sustainable Aquaculture (GS1) (NacSA) regulated by the Marine Products Export Development Authority (MPEDA).

Fishing communities inherently engage in collective action for co-managing the natural resources they have access to (Pretty and Ward, 2001) and communities in Uttara Kannada were no different. Furthermore, studies have shown that collective action and self-organisation together with community leaders and research partnerships can reduce vulnerability to climate change (Martins and Gasalla, 2020) and also promote successful larger-scale fisheries (Gutiérrez, *et al.*, 2011). Social capital, in terms of social networks and institutions, has also been shown to have a strong positive impact on fish trader business performance (Gunakar and Bhatta, 2021). However, a study in Vietnam showed that the conversion of mangrove systems into intensive aquaculture has a strong negative effect on the social networks and livelihoods of mangrove system dependent communities (Orchard *et al.*, 2015). Therefore, the **second leverage point** of this social-ecological system is to improve the social capital (A6) of actors of crab fisheries and crab aquaculture. That consequently can improve networking activities (I8) and information sharing (I2), especially taking into account that fishers hold traditional ecological knowledge and crab farmers could have access to training. Increased social networking activities could also positively influence self-organising activities (I7) such as co-management of natural resources of the resource systems. Those interactions then would maintain high social and ecological performance as resource systems would be sustainably managed. Yet, any intervention should be considered carefully and in collaboration with the local communities involved.

### 6.2.3. Property rights systems and financial support

The objective of chapter two was to explore what limits fisher communities to undertake crab farming and the main barriers were reported to be lack of land (or poor access to it) and lack of finances. Furthermore, less than one third would even consider undertaking such an activity. Unwillingness to be involved in crab farming could also be related to the negative associations linked with shrimp farming. Shrimp aquaculture is responsible for major mangrove destruction on the east coast of India, causing several environmental and social problems for coastal communities (Hein, 2000). An example of encroachment and coastal grabbing has been seen in the Chilika lagoon in Odisha, India, where commercial shrimp farming marginalised thousands of fishers (Nayak, 2014; Nayak and

Berkes, 2010). Similarly to the Chilika lagoon, fisher castes in Uttara Kannada described in chapter two strongly rely on common fisheries resources due to poor access to additional land and support due to institutional caste inequality. Besides, crab farmers interviewed for chapter three were mainly from the non-fishing background. Thus, even not being a focus of this study, it is clear that the complicated caste system and lack of rights and support for fisher castes (Bakshi, 2008), influence their livelihoods and hinder them from diversification. Therefore to consider crab farming as a possible activity for fisher communities, improved access to land (property rights systems GS4) and access to financial support, such as microfinance, is necessary (**third leverage point**). That could also have a wider effect on economic sustainability to local communities and benefit environmental sustainability. However, it is important to remember that any intervention can also cause changes in the wrong direction (Meadows, 2008). Unregulated loans can lead to debts and unconsidered land reforms or attempts to improve property rights can even worsen the already existing inequalities.

### 6.2.4. External factors influencing the social-ecological system

Perceived as a delicacy, green mud crab *S. serrata* is in high demand in domestic and international markets, while the other smaller species, such as *S. tranquebarica*, known as red mud crabs locally, are usually consumed by the local communities. The market demand, particularly, the international market demand, acts like a reinforcing loop (Fig.6.5) – ensuring economic growth, but also can cause great damage (Meadows, 2008). Chapter three showed that a price decrease could be devastating to small-scale crab farmers (Fig.3.5). Yet, market demand in theory has the ability to provide an incentive to fish in a sustainable manner to secure a stable supply (Reddy *et al.*, 2013).

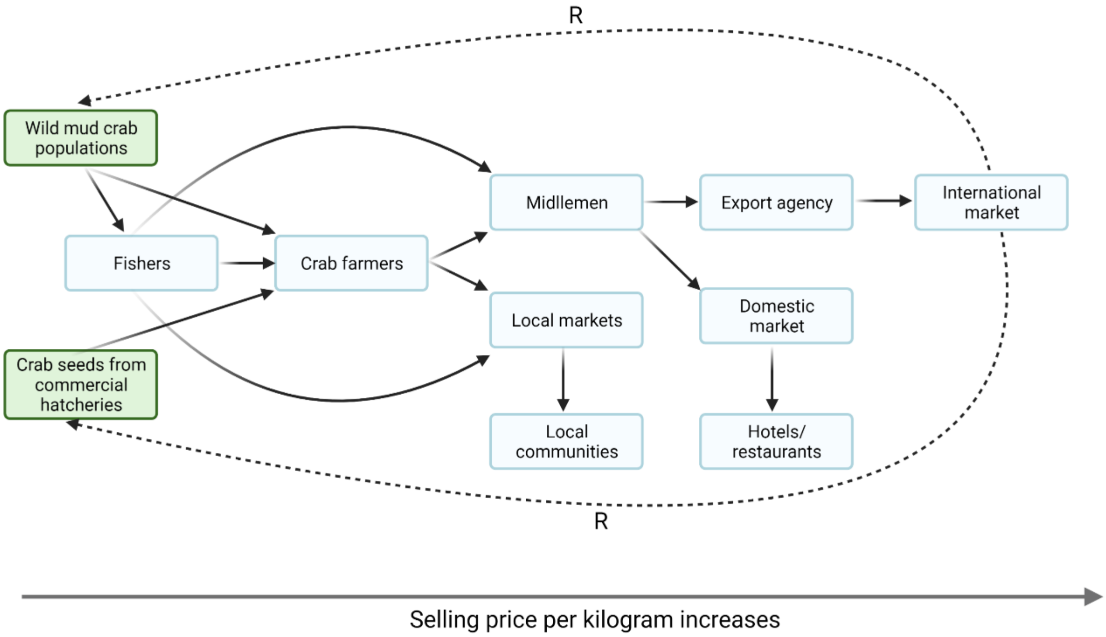


*Figure 6.5. The supply chain of mud crabs with reinforcing feedback loops. The arrow indicates an increase in added value along the supply chain. Created with BioRender.com.*

A study on Pacific red snapper (*Lutjanus peru)*, a relatively slow growing species with a long life span, showed that market-driven size-selective fishing for plate-sized fish together with institutional monitoring increased fishers' revenues and average fish biomass (Reddy *et al.*, 2013). Selective fishing, however, can have negative implications on biodiversity if a certain species is preferred, and can result in changes in sex ratio, biomass, growth and survival (Fenberg and Roy, 2008; Zhou *et al.*, 2010). Mud crab harvesting undoubtedly is already selective for various reasons. Firstly, fishers are mainly harvesting *S. serrata* and might even release the other mud crab species. Secondly, fishers generally use ring nets that would only catch crabs and do not impact fish. Thirdly, ring nets do not harm the animals thus they can be released back into the water. Yet, as mentioned there are no regulations regarding the size and the sex of animals that can be caught. Indiscriminate harvesting of mud crabs of any size, including sub-adults and berried females, are the challenges that need to be overcome in order to ensure sustainable supply (Ali *et al.*, 2020). This, in turn, will be beneficial to fisher communities and crab farmers in the long term. Yet, that requires operational-choice, collective-choice and/or constitutional choice rules (Ostrom, 1990). Acknowledging that poor fisher communities are more concerned about the income they can obtain in the present day rather than having a strategy for the future, the incentive to apply sustainable harvesting practices should come from the actors higher in the supply chain (Fig.6.5). The market demand already is size selective as the price depends on the crab mass and middlemen have the ability to act as 'conservation agents' (Sen and Homechaudhuri, 2017).

Currently, market demand is a positive driver, yet it does hold the potential to cause overexploitation. However, market demand is not the only external factor influencing this social-ecological system. Climate change and pollution from related ecosystems can significantly affect resource units and whole resource systems, thus causing a chain reaction and affecting various components of the social-ecological system. It is clear from the results of chapter four and chapter five that the mud crabs will not be an exception and climate change will impact mud crab fisheries and aquaculture. The gut microbiome study showed that increased water temperatures were associated with decreased bacterial species richness and abundance in adult mud crab guts. Although a deeper investigation is needed, it has been acknowledged that the gut microbiome positively contributes to crustacean physiological and metabolic status and thus warming could compromise it. Besides, mud crab farmers in Andhra Pradesh reported warming to be one of the causes of mass mortality. The results of the mesocosm experiment described in chapter five also corroborated these findings. Warming was shown to cause an increase in oxygen consumption in juvenile mud crabs, indicating higher energy consumption to maintain the balance of the organism. Metabolic rates were also significantly higher in animals exposed to a combination of warming and freshening and especially freshening alone. Thus it is clear that direct climate change effects (warming and freshening) and potentially indirect effects (increased abundance of pathogenic bacteria) induce physiological changes in juvenile mud crabs that can alter their overall fitness at juvenile and consequent life stages.

Climate change has been driven by various reinforcing feedback loops that increase $CO_2$ emissions over time, such as human population growth and increase in energy using capital, which in turn cause global warming, extreme weather events and other adverse effects on human and natural systems (Meadows, 2008). Policy action to adapt and mitigate the impacts of climate change, however, acts as a balancing feedback loop aiming to ensure the balance of the system (Sterman, 2012). The global warming and changes in precipitation caused by $CO_2$ and other greenhouse gas emissions are believed to be largely irreversible for another millennium even in an unlikely zero-emission scenario (Solomon *et al.*, 2009). Therefore the **fourth leverage point** is to adapt to climate change and the impacts it has on fisheries and aquaculture. There undoubtedly are opportunities for adaptation, including biotechnology, management and engineering solutions, localised mitigation, relocation and diversification (Reid *et al.*, 2019), yet firstly current and future challenges need to be acknowledged. In the case of mud crab fisheries and farming, this thesis identified freshening and warming to be the main challenge. However, climate change effects are not isolated events but tend to interact and cause indirect issues, such as harmful algal blooms and increased abundance of pathogenic bacteria, inducing changes in animal physiology and gut microbiome composition.

## 6.3. Achieving sustainable aquaculture

The sustainability of aquaculture as the fastest growing food production sector (FAO, 2020) has been scrutinised over the past decades. Environmental sustainability has been the most controversial aspect and although it was not the main focus of this thesis and the effects on the crabs themselves rather than the environment was investigated, some of the issues were highlighted by the results. Chapter 3 confirmed that mud crab farming as the majority of aquaculture in Asia depends on “trash fish” (Bunlipatanon *et al.*, 2014). However, the current crab farming practices, which require a vast amount of fish, but do not achieve high survival rates, can be deemed as unsustainable. Therefore, there is a need for collaborative, applied research to find alternatives and also investigate fish consumption habits. Furthermore, although currently mud crab farming is not associated with regular application of external nutrients and antibiotics, the recent outbreak of WSV in Andhra Pradesh (CIBA, 2019) and the trend to transform shrimp farms to mud crab farms (personal communication and observation, EA), could see an increase in the use of antibiotics and chemicals. Aquaculture already is one of the main gateways of antimicrobial resistance and puts at risk all the associated ecosystems (Cabello *et al.*, 2016; Preena *et al.*, 2020). Therefore, antibiotic use in mud crab aquaculture and any other aquaculture should be regulated at a local and national level and crab and fish farmers should be educated about such environmental issues by disseminating easily understandable information. As in any food production sector, mud crab farming can have negative impacts on the environment and society if expanded and intensified. However, the results showed that large-scale farming is associated with high economic risks and larger ponds mean higher stocking density and potentially higher mortality rates. Large-scale mud crab farming utilises a lot of resources that are wasted in case of mass mortalities. Thus, crab farming should be promoted as a small-scale livelihood diversification activity, rather than a large-scale commercial enterprise. That could be done with a help of local and national regulations on farm size, limitations to the number of crabs allowed to purchase from the hatchery and involvement of middlemen as 'conservation agents' (Sen and Homechaudhuri, 2017).

Assessing the sustainability of aquaculture is a difficult task because it is such a complex and multi-faceted concept involving many technical, biological and socio-economic factors and trade-offs (Boyd *et al.*, 2020), but it should be constantly challenged as otherwise the consequences, especially for the more marginalised communities, could be devastating.

## 6.4. Conclusions

This thesis aimed to assess the suitability of the mud crab *Scylla serrata* as a sustainable livelihood resource for local communities in southwest India. This interdisciplinary assessment showed that there are several barriers that hinder crab fisheries and crab aquaculture, and the social-ecological system these resource systems are a part of, to be environmentally, economically and socially sustainable. The first barrier that was reported both by the fishers and crab farmers is the seemingly decreasing wild mud crab populations and the unavailability of crab seedlings from commercial hatcheries. This affects environmental sustainability as constant pressure on wild populations can lead to overexploitation and without monitoring activities it is difficult to assess the state of the mud crab populations in southwest India. The second barrier is the lack of financial support and poor access to land. These factors were found to be especially limiting for fisher communities yet were also significant barriers for crab farmers. The third barrier is the lack of knowledge or rather the lack of information sharing. Fishers possess traditional ecological knowledge but have limited access to formal training. On the contrary, crab farmers as entrepreneurs are more likely to access training, yet not have inherent knowledge. Last but not least barrier is the threat of climate change, in particular, global ocean warming and freshening. Crab fishers and farmers reported high water temperatures to be one of the reasons for mass crab mortality. Furthermore, mesocosm experiments showed physiological changes as a response to warming and freshening in juvenile mud crabs and changes in gut microbiome composition due to increased temperature were identified. Meanwhile, market demand serves as an incentive to ensure a sustainable supply of mud crabs.

By applying systems thinking, it was possible to identify four points of intervention or leverage points that could be the key factors in achieving the sustainability of this social-ecological system. The **first leverage poin**t being improving access to hatchery reared mud crab seedlings. To achieve this more commercial hatcheries should be established and research on how to optimise this process should be carried out. Simultaneously, it would be important to ensure access to commercial seedlings for both large and small-scale crab farmers, and also for those fishers who are considering crab farming as livelihood diversification. The **second leverage point** of this social-ecological system – improving the social capital of all the actors involved – might be the most significant one. Social capital includes trust, norms, reciprocity and social networks, all of which can contribute to achieving sustainability in various ways. For instance, co-management based on social network interactions can contribute to environmental sustainability and self-help groups can increase economic and social sustainability for local communities. The **third leverage point** is improving access to land for aquaculture purposes, especially for fishing communities, and offer financial support in form of subsidies or low interest rate loans. The **final leverage point** is facilitating adaptation to the projected effects of climate change that will not only affect mud crabs but any resource system in this social-ecological system. Yet, any intervention has to be carefully considered together with actors of the resource systems in question.

Overall, the findings of this thesis indicate that mud crab *S. serrata* fishing and farming currently could not be described as fully sustainable. However, by applying interdisciplinary analytical tools such as the social-ecological system framework and systems thinking, it was possible to identify the limits to the current system and also the key points of intervention that achieve economic, ecological and social sustainability of mud crabs as a livelihood resource. Mud crab fisheries and aquaculture have the potential to be sustainable resource systems, yet require changes in governance systems and interactions carried out by actors to reach this potential and calls for collaborative research to uncover the best sustainable practices.

## 6.5. Opportunities for further research

There are areas of this study that would require further research to fully unveil all the aspects influencing the suitability of the mud crab *S. serrata* as a sustainable livelihood resource:

1. Assessment of mud crab stocks and determining maximum sustainable yield could help to obtain a better understanding of whether mud crabs are fully exploited.

2. By using participatory action research (PAR) investigate traditional ecological knowledge of fishers and how that could be used to maximise the potential of those local fisher communities.

3. Explore in more detail fishers' perceptions of crab farming and aquaculture in general and identify mechanisms to improve access to resources required for mud crab farming.

4. Assess the sustainability of “trash fish/low value fish” use as feed in the mud crab and other aquaculture, by applying similar interdisciplinary approach – assess and model the stocks of such fish, conduct an economic assessment and explore the fish consumption.

5. Assess how ocean acidification and hypoxia could impact mud crabs in the future by simulating projected carbon dioxide ($CO_2$) and oxygen ($O_2$) concentrations in laboratory conditions and by measuring dissolved $CO_2$ and $O_2$ in aquaculture ponds.

6. Further investigate how temperature and other physiochemical factors affect the gut microbiome and its functions in the mud crab *Scylla serrata*.

# References

Abate, T. G., Nielsen, R., Nielsen, M., Drillet, G., Jepsen, P. M., & Hansen, B. W. (2015). Economic feasibility of copepod production for commercial use: Result from a prototype production facility. *Aquaculture*, 436, 72–79.

Acemoglu, D. & Robinson, J. (2008). *The Role of Institutions in Growth and Development. Commission on Growth and Development*. The World Bank, New York.

Adger, W. N. (2006). Vulnerability. *Global Environmental Change*, 16(3), 268–281.

Agbayani, R. F. (2001). Production economics and marketing of mud crabs in the Philippines. *Asian Fisheries Science*, 14, 201–210.

Alberts-Hubatsch, H., Lee, S. Y., Meynecke, J. O., Diele, K., Nordhaus, I., & Wolff, M. (2016). Life-history, movement, and habitat use of *Scylla serrata* (Decapoda, Portunidae): current knowledge and future challenges. *Hydrobiologi*a, 763(1), 5–21.

Alberts-Hubatsch, H., Yip Lee, S., Nordhaus, I., Diele, K., & Wolff, M. (2014). Microhabitat use of early benthic stage mud crabs, *Scylla serrata* (Forskål, 1775), in Eastern Australia. *Journal of Crustacean Biology*, 34(5), 604–610.

Aldridge, A. & Levine, K. (2001). *Surveying the social world. Principles and practice in survey research*. Open University Press, Philadelphia.

Ali, M. Y., Hossain, M. B., Sana, S., Rouf, M. A., Yasmin, S., & Sarower, M. G. (2020). Identifying peak breeding season and estimating size at first maturity of mud crab (*Scylla olivacea*) from a coastal region of Bangladesh. *Heliyon*, 6(6), e04318.

Allan, J. D., Abell, R., Hogan, Z., Revenga, C., Taylor Brad W., Welcomme, R. L., & Winemiller, K. (2005). Overfishing of Inland Waters. *BioScience*, 55(12), 1041.

Allison, E. H., & Ellis, F. (2001). The livelihoods approach and management of small-scale fisheries. *Marine Policy*, 25(5), 377–388.

Allison, E. H., & Horemans, B. (2006). Putting the principles of the Sustainable Livelihoods Approach into fisheries development policy and practice. *Marine Policy*, 30(6), 757–766.

Allison, E.H., Adger, W.N., Badjeck, M-C., Brown, K., Conway, D., Dulvy, N.K., Halls, A., Perry, A. & Reynolds, J.D. (2005). *Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisherfolk living in poverty*. Report no. R4778J, Fisheries Management Science Programme, DfID, London.

Anderies, John M., Janssen, M. A., & Ostrom, E. (2004). A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. *Ecology and Society*, 9(1), 1–19.

Andriesse X., Bakker H. & Weisbeek P. (1990). Analysis of Nitrate Reduction Genes in Cyanobacteria. In Ullrich W.R., Rigano C., Fuggi A., Aparicio P.J. (Eds) *Inorganic Nitrogen in Plants and Microorganisms* (pp.303-307). Springer, Berlin, Heidelberg.

Anger, K. (2003). Salinity as a key parameter in the larval biology of decapod crustaceans. *Invertebrate Reproduction and Development*, 43(1), 29–45.

Anilkumar, P. 2017. Mangrove Crab *Scylla serrata* stock enhancement by Ranching, Pen and Tide fed Impoundments in mangrove ecosystem of

Sindhudurg District, Maharashtra through empowerment of traditional fishermen. *Ela Journal of Forestry and Wildlife*, 6(1), 308-316.

Ankamah-Yeboah, I., Jacobsen, J. B., & Olsen, S. B. (2018). Innovating out of the fishmeal trap: The role of insect-based fish feed in consumers' preferences for fish attributes. *British Food Journal,* 120(10), 2395-2410.

Anokyewaa, M. A., & Asiedu, B. (2019). Economic Analysis of Small-Scale Aquaculture Enterprise in Ghana; a Case Study of Sunyani Municipality. *Asian Journal of Fisheries and Aquatic Research*, March, 1–12.

Apprill, A. (2017). Marine Animal Microbiomes: Toward Understanding Host–Microbiome Interactions in a Changing Ocean. *Frontiers in Marine Science*, 4(July), 1–9.

Aquino, J.I.L. (2018). Promoting Responsible Aquaculture for the Sustainable Production of Soft-shell Crabs. *Fish for the People*, 16(3), 46-51.

Arndt, D., Xia, J., Liu, Y., Zhou, Y., Guo, A.C., Cruz, J.A., Sinelnikov, I., Budwill, K., Nesbø, C.L. & Wishart, D.S. (2012). METAGENassist: A comprehensive web server for comparative metagenomics Nucleic Acids Research 2012 Jul 40 (Web Server issue):W88-95

Arnold, R. D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. *Procedia Computer Scienc*e, 44, 669–678.

Arriola, F. J. (1940). A preliminary study of the life history of *Scylla serrata* (Forskal). *The Phillipine Journal of Scienc*e, 73, 437–456.

Asche, F., Bellemare, M. F., Roheim, C., Smith, M. D., & Tveteras, S. (2015). Fair Enough? Food Security and the International Trade of Seafood. *World Development*, 67(2010), 151–160.

Ashaletha, S. (2018). Prospects of micro-financing in fisheries sector. In Suresh, A., Sajeev, M.V. and Rejula, K. (Eds), *Extension management techniques for up-scaling technology dissemination in fisheries*. ICAR- Central Institute of Fisheries Technology.

Ashley, C. & Carney, D. (1999). *Sustainable livelihoods: Lessons from early experience*. London, UK: Department for International Development.

Ashton, E. (2008). The impact of shrimp farming on mangrove ecosystems. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 3(003).

Aswani, S., Lemahieu, A. & Sauer, W.H.H. (2018). Global trends of local ecological knowledge and future implications. *PLoS ONE* 13(4): e0195440.

Azra, M. N., & Ikhwanuddin, M. (2015). Larval culture and rearing techniques of commercially important crab, *Portunus pelagicus* (Linnaeus, 1758): Present status and future prospects. *Songklanakarin Journal of Science and Technology*, 37(2), 135–145.

Bäckhed, F., Ding, H., Wang, T., Hooper, L. V., Gou, Y. K., Nagy, A., Semenkovich, C. F., & Gordon, J. I. (2004). The gut microbiota as an environmental factor that regulates fat storage. *Proceedings of the National Academy of Sciences of the United States of America*, 101(44), 15718–15723.

Bag, N., Bimal, S. M., & Mal, C. (2014). Economic feasibility of intensive aquaculture integrated with irrigation system. *Indian Journal of Fisheries*, 61(4), 72–78.

Bakshi, A. (2008). Social Inequality in Land Ownership in India: A study with particular reference to West Bengal. *Social Scientist*, 36(9/10), 95–116.

Balaguru, K., Foltz, G. R., Leung, L. R., & Emanuel, K. A. (2016). Global warming-induced upper-ocean freshening and the intensification of super typhoons. *Nature Communications*, 7, 1–8.

Balasubramanian, C. P., Cubelio, S. S., Mohanlal, D. L., Ponniah, A. G., Kumar, R., Bineesh, K. K., Ravichandran, P., Gopalakrishnan, A., Mandal, A., & Jena, J. K. (2016). DNA sequence information resolves taxonomic ambiguity of the common mud crab species (Genus *Scylla*) in Indian waters. *Mitochondrial DNA*, 27(1), 270–275.

Barrett, C.B., Reardon, T. & Webb, P. (2001). Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics and policy implications. *Food Policy,* 26, 315–331.

Bastos, A. M., Lima, J. F., & Tavares-Dias, M. (2018). Effect of increase in temperature on the survival and growth of *Macrobrachium amazonicum* (Palaemonidae) in the Amazon. *Aquatic Living Resources*, 31, 21.

Basurto, X., Gelcich, S., & Ostrom, E. (2013). The social-ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change*, 23(6), 1366–1380.

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. (2008). *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat.

Baulch, B., & Hoddinott, J. (2000). Economic mobility and poverty dynamics in developing countries. *Journal of Development Studies*, 36(6), 1–24.

Baylon, J. C. (2010). Effects of Salinity and Temperature on Survival and Development of Larvae and Juveniles of the Mud Crab, *Scylla serrata*

(Crustacea: Decapoda: Portunidae). *Journal of the World Aquaculture Society*, 41(6), 858–873.

Bebbington, A. (1999). Capitals and capabilities: A framework for analyzing peasant viability, rural livelihoods and poverty. *World Development*, 27(12), 2021–2044.

Belkaid, Y., & Hand, T. W. (2014). Role of the microbiota in immunity and inflammation. *Cell*, 157(1), 121–141.

Belton B., Ahmed N. & Murshed-e-Jahan K. (2014). *Aquaculture, employment, poverty, food security and well-being in Bangladesh: A comparative study*. Penang, Malaysia: CGIAR Research Program on Aquatic Agricultural Systems. Program Report: AAS-2014-39.

Belton, B., Bush, S. R., & Little, D. C. (2018). Not just for the wealthy: Rethinking farmed fish consumption in the Global South. *Global Food Security*, 16, 85–92.

Belton, B., Padiyar, A., Ravibabu, G., & Gopal Rao, K. (2017). Boom and bust in Andhra Pradesh: Development and transformation in India’s domestic aquaculture value chain. *Aquaculture*, 470, 196–206.

Béné, C. (2009). Are fishers poor or vulnerable? Assessing economic vulnerability in small-scale fishing communities. *Journal of Development Studies*, 45(6), 911–933.

Béné, C. (2015). The Good, the Bad and the Ugly: Discourse, Policy Controversies and the Role of Science in the Politics of Shrimp Farming. *Development Policy* Review, 23 (5), 585–614.

Beneduzi, A., Peres, D., Vargas, L. K., Bodanese-Zanettini, M. H., & Passaglia, L. M. P. (2008). Evaluation of genetic diversity and plant growth promoting activities of nitrogen-fixing bacilli isolated from rice fields in South Brazil. *Applied Soil Ecology*, 39(3), 311–320.

Berkes, F. & Folke, C. (1998). *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press, Cambridge, UK.

Berkes, F., Colding, J. & Folke, C., 2010. Rediscovery of Traditional Ecological Knowledge as Adaptive Management. *Ecological Applications*, 10(5), 1251–1262.

Besley, T., Leight, J., Pande, R., & Rao, V. (2016). Long-run impacts of land regulation: Evidence from tenancy reform in India. *Journal of Development Economics*, 118, 72–87.

Beveridge, M. C. M., Thilsted, S. H., Phillips, M. J., Metian, M., Troell, M., & Hall, S. J. (2013). Meeting the food and nutrition needs of the poor: The role of fish and the opportunities and challenges emerging from the rise of aquaculture. *Journal of Fish Biology*, 83(4), 1067–1084.

Bhat, M., Nayak, V.N., Subash Chandran, D.M. & Ramachandra, V.T. (2012). *Impact of hydro-electric dams on fisheries in the Sharavati estuary of Uttara Kannada district, South-West India.* Lake 2012: National Conference on Conservation and Management of Wetland Ecosystems.

Bhatta, R., & Bhat, M. (1998). Impacts of aquaculture on the management of estuaries in India. *Environmental Conservation*, 25(2), 109–121.

Bik, E. M., Costello, E. K., Switzer, A. D., Callahan, B. J., Holmes, S. P., Wells, R. S., Carlin, K. P., Jensen, E. D., Venn-Watson, S., & Relman, D. A. (2016). Marine mammals harbor unique microbiotas shaped by and yet distinct from the sea. *Nature Communications*, 7.

Binder, C. R., Hinkel, J., Bots, P. W. G., Pahl, C., Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of Frameworks for Analyzing Social-ecological Systems.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J.M., *et al.* (2007). Observations: oceanic climate change and sea level. In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M. *et al* (Eds.) *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 385–432). Cambridge: Cambridge Univ. Press.

Blythe, J., Flaherty, M., & Murray, G. (2015). Vulnerability of coastal livelihoods to shrimp farming: Insights from Mozambique. *Ambio*, 44(4), 275–284.

Bonine, K. M., Bjorkstedt, E. P., Ewel, K. C., & Palik, M. (2008). Population characteristics of the mangrove crab *Scylla serrata* in Kosrae, Federated States of Micronesia: Effects of harvest and implications for management. *Pacific Science*, 62(1), 1–19.

Boonsanit, P., & Pairohakul, S. (2021). Effects of salinity on haemolymph osmolality, gill Na+/K+ ATPase and antioxidant enzyme activities in the male mud crab *Scylla* olivacea (Herbst, 1796). *Marine Biology Research*, 1–12.

Bostock, J. (2011). The application of science and technology development in shaping current and future aquaculture production systems. *Journal of Agricultural Scienc*e, 149(S1), 133–141.

Bostock, John, McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., & Corner, R. (2010).

Aquaculture: Global status and trends. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), 2897–2912.

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., McNevin, A.A., Tacon, A.G.J., Teletchea, F., Tomasso Jr., G,R, Tucker, C.S. & Valenti, W. C. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, 51(3), 578-633.

Boyd, C.E. & Pillai, V.K. (1985). *Water quality management in aquaculture*. CMFRI Special Publication, Number 22. Issued on the occasion of the workshop on Water Quality Management in Aquaculture organised by the Centre of Advanced Studies in Mariculture, Central Marine Fisheries Research Institute, Indian Council of Agricultural Research, Cochin, 10-13 December 1984.

Braker, G., & Conrad, R. (2011). Diversity, structure, and size of N2O-producing microbial communities in soils – What matters for their functioning? *Adv. Appl. Microb*. 75, 33–70.

Brestoff, J.R. & Artis, D. (2013). Commensal bacteria at the interface of host metabolism and the immune system. *Nat Immunol.,* 14(7), 676–684.

Brown, I. W., 1993. Mangrove crabs. In Wright, A., & L. Hill (Eds), *Nearshore Marine Resources of the South Pacific* (pp. 609–642). Institute of Pacific Studies (Suva), Forum Fisheries Agency (Honiara) and the International Centre for Ocean Development (Canada).

Bunlipatanon, P., Songseechan, N., Kongkeo, H., Abery, N. W., & De Silva, S. S. (2014). Comparative efficacy of trash fish versus compounded commercial feeds in cage aquaculture of Asian seabass (Lates calcarifer)(Bloch) and tiger grouper (Epinephelus fuscoguttatus)(Forsskål). *Aquaculture Research*, 45(3), 373-388.

Burge, C. A., Mark Eakin, C., Friedman, C. S., Froelich, B., Hershberger, P. K., Hofmann, E. E., Petes, L. E., Prager, K. C., Weil, E., Willis, B. L., Ford, S. E., & Harvell, C. D. (2014). Climate change influences on marine infectious diseases: Implications for management and society. *Annual Review of Marine Science*, 6, 249–277.

Burrel, P.C., Phalen, C.M. & Hovanec, T.A. (2001). Identification of Bacteria Responsible for Ammonia Oxidation in Freshwater Aquaria. *Applied and Environmental Microbiology*, 67 (12), 5791-5800.

Butt, R. L., & Volkoff, H. (2019). Gut microbiota and energy homeostasis in fish. *Frontiers in Endocrinology*, 10, 6–8.

Cabello, F. C., Godfrey, H. P., Buschmann, A. H., & Dölz, H. J. (2016). Aquaculture as yet another environmental gateway to the development and globalisation of antimicrobial resistance. *The Lancet Infectious Diseases*, 16(7), e127-e133.

Campbell, J., Whittingham, E. and Townsley, P. (2006). Responding to coastal poverty: should we be doing things differently or doing different things? In: Hoanh, C., Tuong, T., Gowing, J., Hardy, B. (Eds.) *Environment and livelihoods in tropical coastal zones. (pp.274-292)*. CABI, Wallingford, UK.

Carlet, J. (2012). The gut is the epicentre of antibiotic resistance. *Antimicrobial Resistance and Infection Control*, 1, 1–7.

Central Statistics Office (2011). *Manual on fishery statistics. CSO-MFS-2011*. Government of India. Ministry of Statistics and Programme Implementation, Sansad Marg, New Delhi.

Cha, J. H., Rahimnejad, S., Yang, S. Y., Kim, K. W., & Lee, K. J. (2013). Evaluations of Bacillus spp. As dietary additives on growth performance, innate immunity and disease resistance of olive flounder (Paralichthys olivaceus) against streptococcus iniae and as water additives. *Aquaculture,* 402–403, 50–57.

Chambers, R., & Conway, G. R. (1991). Sustainable rural livelihoods: practical concepts for the 21st century. Ids Discussion Paper, 296. Institute of Development Studies, University of Sussex, Brighton.

Chauhan, C. P. S. (2008). Education and caste in India. *Asia Pacific Journal of Education*, 28(3), 217–234.

Chen, J. C., & Chia, P. G. (1996). Oxygen uptake and nitrogen excretion of juvenile *Scylla serrata* at different temperature and salinity levels. *Journal of Crustacean Biology*, 16(3), 437-442.

Chen, J., Sun, R., Pan, C., Sun, Y., Mai, B., & Li, Q. X. (2020). Antibiotics and food safety in aquaculture. *Journal of Agricultural and Food Chemistry*, 68(43), 11908-11919.

Cheung, W. W. L., Jones, M. C., Lam, V. W. Y., D Miller, D., Ota, Y., Teh, L., & Sumaila, U. R. (2017). Transform high seas management to build climate resilience in marine seafood supply. *Fish and Fisheries*, 18(2), 254–263.

Cheung, W. W., & Frölicher, T. L. (2020). Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, 10(1), 1-10.

Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge*, 4(4), 10.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D. , Payne, A.J., Pfeffer, W.T., Stammer, D. and Unnikrishnan A.S., (2013). *Sea level change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

CIBA (2018). *Training Calendar 2018-2019*. ICAR-Central Institute of Brackishwater Aquaculture. Chennai, India. [Online] Available at: http://www.ciba.res.in/stuff/Training%20Calendar%202018-19.pdf (Accessed on 3 December 2018).

CIBA (2019). *Annual Report 2018-2019*. ICAR-Central Institute of Brackishwater Aquaculture, Chennai, India.

CIBA (2020). Central Institute of Brackishwater Aquaculture. About us. [Online] Available at: http://www.ciba.res.in/?page_id=447 (Accessed 15 March 2021)/

Cinner, J. E., & Bodin, Ö. (2010). Livelihood diversification in tropical coastal communities: A network-based approach to analyzing “livelihood landscapes.” *PLoS ONE*, 5(8).

Clarke, K., & Gorley, R. (2006). *PRIMER v6: User Manual/Tutorial*. Plymouth Routines in Multivariate Ecological Research. Plymouth: Primer-E Ltd.

CMFRI (2010). *Marine Fisheries Census 2010*. Kochi, India. Central Marine Fisheries Research Institute.

CMFRI (2018). *Training courses.* ICAR-Central Marine Fisheries Research Institute. Kochi, India. [Online] Available at: http://www.cmfri.org.in/training-courses (Accessed 3 December 2018).

Coastal Aquaculture Authority (2021). Shrimp farms. [Online]. Available at: http://caa.gov.in/farms.html (Accessed 2 March 2021).

Cogo, G. B., Biasi, C., Severo, E. S., Loro, V., & Santos, S. (2018). Environmental warming induces behavioral and metabolic changes in a freshwater crustacean - Aeglids as a model organism. *Annales de Limnologie*, 54(7).

Comte, L., Buisson, L., Daufresne, M., & Grenouillet, G. (2013). Climate-induced changes in the distribution of freshwater fish: Observed and predicted trends. *Freshwater Biology*, 58(4), 625–639.

Cooke, S. J., Bergman, J. N., Madliger, C. L., Cramp, R. L., Beardall, J., Burness, G., ... & Chown, S. L. (2021). One hundred research questions in conservation physiology for generating actionable evidence to inform conservation policy and practice. *Conservation Physiology*, 9(1), coab009.

Cordeiro, C. M., & Sogn-Grundvåg, G. (2019). An Integral Systems Theory Perspective of Interdisciplinary Collaboration: The Example of CATCH, a Capture-Based Aquaculture Research Project for Quality Norwegian Cod Products. *Academic Journal of Interdisciplinary Studies*, 8(1), 19–35.

Cornejo-Granados, F., Gallardo-Becerra, L., Leonardo-Reza, M., Ochoa-Romo, J. P., & Ochoa-Leyva, A. (2018). A meta-analysis reveals the environmental and host factors shaping the structure and function of the shrimp microbiota. *PeerJ*, 6, e5382.

da Silva Vianna, B., Miyai, C. A., Augusto, A., & Costa, T. M. (2020). Effects of temperature increase on the physiology and behavior of fiddler crabs. *Physiology & Behavior*, 215, 112765.

Dabbadie, L., Aguilar-Manjarrez, J., Beveridge, M.C.M., Bueno, P.B., Ross, L.G. & Soto, D. (2018). Effects of climate change on aquaculture: drivers, impacts and policies. In *Impacts of climate change on fisheries and aquaculture.* Food and Agriculture Organization of the United Nations (FAO), Rome.

Dao, T. (2020). India unveils financial plan to support fisheries sector. *SeafoodSourc*e (May 19). [Online] Available at: https://www.seafoodsource.com/news/supply-trade/india-unveils-financial-plan-to-support-fisheries-sector. (Accessed on 15 December 2020).

Das, M. K., Sharma, A. P., Sahu, S. K., Srivastava, P. K., & Rej, A. (2013). Impacts and vulnerability of inland fisheries to climate change in the Ganga River system in India. *Aquatic Ecosystem Health and Management*, 16(4), 415–424.

Daviglus, M., Sheeshka, J., & Murkin, E. (2002). Health Benefits from Eating Fish. *Comments on Toxicology*, 8:4-6, 345-374.

Davis, A., & Ruddle, K. (2012). Massaging the misery: Recent approaches to fisheries governance and the betrayal of small-scale fisheries. *Human Organization*, 71(3), 244–254.

De Senerpont Domis, L. N., Van De Waal, D. B., Helmsing, N. R., Van Donk, E., & Mooij, W. M. (2014). Community stoichiometry in a changing world: Combined effects of warming and eutrophication on phytoplankton dynamics. *Ecology*, 95(6), 1485–1495.

Demopoulos, A. W. J., Cormier, N., Ewel, K. C., & Fry, B. (2008). Use of multiple chemical tracers to define habitat use of Indo-Pacific mangrove crab, *Scylla serrata* (Decapoda: Portunidae). *Estuaries and Coasts*, 31(2), 371–381.

Deng, Y., Cheng, C., Xie, J., Liu, S., Ma, H., Feng, J., Su, Y., & Guo, Z. (2019). Coupled changes of bacterial community and function in the gut of mud crab

(*Scylla paramamosain*) in response to Baimang disease. *AMB Express*, 9(1), 1–9.

Deng, Y., Xu, L., Chen, H., Liu, S., Guo, Z., Cheng, C., Ma, H. and Feng, J. (2020). Prevalence, virulence genes, and antimicrobial resistance of *Vibrio* species isolated from diseased marine fish in South China. *Scientific Reports*, 10(1), 1-8.

Department for International Development (1999). *Sustainable Livelihoods Guidance Sheets*. Department for International Development, London, United Kingdom.

Department of Animal Husbandry, Dairying and Fisheries (2018). *Basic animal husbandry and fisheries statistics 2018*. Government of India. Ministry of Agriculture and Farmers Welfare. Krishi Bhawan, New Delhi, India.

Department of Animal Husbandry, Dairying and Fisheries (2019). *Annual Report 2018-19. Government of India*. Ministry of Agriculture and Farmers Welfare. Krishi Bhawan, New Delhi, India.

Department of Fisheries (2013). *Mud Crab*. Department of Fisheries fact sheet No.28. Government of Western Australia.

Department of Fisheries (2018). *Crab, mud (green and brown).* Western Australian recreational fishing rules. Government of Western Australia. [Online] Available at: http://rules.fish.wa.gov.au/Species/Index/46 (Accessed 7 November 2018).

Desai, S. & Banerji, M. (2008). Negotiated Identities: Male Migration and Left-Behind Wives in India. *Journal of Population Research*, 25(3), 337-355.

Development Initiatives (2018). 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives

Di Leo, G., & Sardanelli, F. (2020). Statistical significance: p value, 0.05 threshold, and applications to radiomics—reasons for a conservative approach. *European radiology experimental*, 4(1), 1-8.

Ding, Z. F., Cao, M. J., Zhu, X. S., Xu, G. H., & Wang, R. L. (2017). Changes in the gut microbiome of the Chinese mitten crab (*Eriocheir sinensis*) in response to White spot syndrome virus (WSSV) infection. *Journal of Fish Diseases*, 40(11), 1561–1571.

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other $CO_2$ problem. *Annual Review of Marine Science*, 1, 169–192.

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., Grebmeier, J. M., Hollowed, A. B., Knowlton, N., Polovina, J., Rabalais, N. N., Sydeman, W. J., & Talley, L. D. (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, 4, 11–37.

Dong, J., Li, X., Zhang, R., Zhao, Y., Wu, G., Liu, J., Zhu, X., & Li, L. (2018). Comparative analysis of the intestinal bacterial community and expression of gut immunity genes in the Chinese Mitten Crab (*Eriocheir sinensis*). *AMB Express*, 8(1).

Dudley, N., & Alexander, S. (2017). Agriculture and biodiversity: a review. *Biodiversity*, 18(2-3), 45-49.

ECFC (2005). *Empowerment of Coastal Fishing Communities for Livelihood Security (BGD/97/017). A livelihood Analysis.* The Technical Advisory Group of ECFC. GOB/UNDP/FAO Project. October 2005.

Edwards, P. (2000). Aquaculture, poverty impacts and livelihoods. *ODI Natural Resource Perspectives*, 56, 1–4.

Egerton, S., Culloty, S., Whooley, J., Stanton, C., & Ross, R. P. (2018). The gut microbiota of marine fish. *Frontiers in Microbiology*, 9, 1–17.

Eigaard, O. R., Marchal, P., Gislason, H., & Rijnsdorp, A. D. (2014). Technological Development and Fisheries Management. *Reviews in Fisheries Science and Aquaculture*, 22(2), 156–174.

Ellis, F. (2000). *Rural livelihoods and diversity in developing countries*. Oxford: Oxford University Press.

El-Sayed, A., & Kamel, M. (2020). Climatic changes and their role in emergence and re-emergence of diseases. *Environmental Science and Pollution Research*, 27(18), 22336–22352.

Estampador E., P. (1949). Studies on *Scylla* (Crustacea: Portunidae). I. Revision of the genus. *Philippine Journal of Science*, 78, 95–108.

FAO (1988). *Definition of aquaculture*. Seventh Session of the IPFC Working Party of Expects on Aquaculture, IPFC/WPA/WPZ, p.1-3, RAPA/FAO, Bangkok.

FAO (2003). *Myanmar Aquaculture and Inland Fisheries*. RAP Publication 2003/18. Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific, Bangkok, pp.62.

FAO (2009). *Measuring the contribution of small-scale aquaculture. An assessment*. FAO Fisheries and Aquaculture Technical Paper 534. Rome, pp.195.

FAO (2011). *Review of the state of world marine fishery resources*. FAO Fisheries and Aquaculture Technical Paper No. 569. Rome.

FAO (2016). *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all*. Rome. 200 pp.

FAO (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. Rome.

FAO (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in action*. Rome.

FAO, IFAD, UNICEF, WFP & WHO (2019). *The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns*. Rome, FAO.

Fargione, J. E., & Tilman, D. (2005). Diversity decreases invasion via both sampling and complementarity effects. *Ecology Letters*, 8(6), 604–611.

Fargione, J., Brown, C. S., & Tilman, D. (2003). Community assembly and invasion: An experimental test of neutral versus niche processes. *Proceedings of the National Academy of Sciences of the United States of America*, 100(15), 8916–8920.

Farrington, J. (2001). *Sustainable livelihoods, rights and the new architecture of aid*. Natural Resource Perspectives 69. Overseas Development Institute, London.

Fenberg, P. B., & Roy, K. (2008). Ecological and evolutionary consequences of size-selective harvesting: How much do we know? *Molecular Ecology*, 17(1), 209–220.

Ferdoushi, Z., & Guo, Z. X. (2010). Economic Analysis of Traditional Mud Crab (*Scylla* Sp.) Fattening in Bangladesh. *Marine. Res. Aqua*., 1(1), 5–13.

Ferrão-Filho, A. D. S., & Kozlowsky-Suzuki, B. (2011). Cyanotoxins: Bioaccumulation and effects on aquatic animals. *Marine Drugs*, 9(12), 2729–2772.

Fielder, D. &Allan, G. (2004). Executive summary and recommendations. In G. Allan and D. Fielder (Eds.), *Mud crab aquaculture in Australia and Southeast Asia* (pp. 61–62). ACIAR Working Paper No. 54, 2004 of Conference.

Fike, D.A., Bradley, A.S. & Leavitt, W.D. (2016). Geomicrobiology of sulfur. In Ehrlich, H.L., Newman, D.K., Kappler A. (Eds.), *Ehrlich's Geomicrobiology*, 6th edition. Taylor and Francis Group, Boca Raton.

Filipski, M., & Belton, B. (2018). Give a Man a Fishpond: Modeling the Impacts of Aquaculture in the Rural Economy. *World Development*, 110, 205–223.

Forest Survey of India (2017). *Mangrove Cover. India State of Forest Report 2017*. Ministry of Environment, Dehradun, India.

Foucreau, N., Cottin, D., Piscart, C., & Hervant, F. (2014). Physiological and metabolic responses to rising temperature in *Gammarus pulex* (Crustacea) populations living under continental or Mediterranean climates. *Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology*, 168, 69–75.

Fraune, S., & Bosch, T. C. G. (2007). Long-term maintenance of species-specific bacterial microbiota in the basal metazoan Hydra. *Proceedings of the National Academy of Sciences of the United States of America*, 104(32), 13146–13151.

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., & Jensen, O. P. (2019). Impacts of historical warming on marine fisheries production. *Science*, 363, 979–983.

Freeman, M., Groom, B., & Spackman, M. (2018). *Social Discount Rates for Cost-Benefit Analysis: A Report for HM Treasury*. A summary report from two workshops on recent advances in social discounting practice and theory. [Online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685904/Social_Discount_Rates_for_Cost-Benefit_Analysis_A_Report_for_HM_Treasury.pdf (Accessed on 15 December 2020).

Friedrich, C. G., Rother, D., Bardischewsky, F., Quentmeier, A. & Fischer, J. (2001). Oxidation of reduced inorganic sulfur compounds by bacteria: emergence of a common mechanism? *Applied and Environmental Microbiology*, 67(7), 2873–2882.

Frölicher, T. L., & Laufkötter, C. (2018). Emerging risks from marine heat waves. *Nature Communications*, 9(1), 1-4.

Fujii, H., Sakakura, Y., Hagiwara, A., Bostock, J., Soyano, K., & Matsushita, Y. (2017). Research and development strategy for fishery technology innovation for sustainable fishery resource management in north-east Asia. *Sustainability*, 10(1).

Ganesh, K., Thampi Sam Raj, Y.C., Perumal, A., Srinivasan, P. & Sethuramalingam, A. (2015). Breeding, Larval Rearing and Farming of Mangrove Crab, *Scylla serrata* (Forskal, 1775) In Perumal, P., Thirunavukkarasu, A.R. & Santhanam, P. (Eds.), *Advances in Marine and Brackishwater Aquaculture* (pp. 163-172). Springer India.

Godhe, A., Narayanaswamy, C., Klais, R., Moorthy, K. S. V., Ramesh, R., Rai, A., & Reddy, H. R. V. (2015). Long-term patterns of net phytoplankton and hydrography in coastal SE Arabian Sea: What can be inferred from genus level data? *Estuarine, Coastal and Shelf Science*, 162, 69–75.

Golden, C. (2016). Are farmed fish just for the wealthy? Golden *et al.* reply. *Nature*, 538(7624), 171.

Gomez-Gil, B., Roque, A., & Turnbull, J. F. (2000). The use and selection of probiotic bacteria for use in the culture of larval aquatic organisms. *Aquaculture*, 191(1–3), 259–270.

Government of Karnataka (2016). *Fisheries Department. Introduction*. [Online] Available at: http://www.karnataka.gov.in/fisheries/english/Pages/Introduction.aspx (Accessed 10 December 2019).

Gowing, J.W., Tuong, T.P., Hoanh, C.T. &Khiem, N.T. (2006). Social and environmental impact of rapid change in coastal zone of Vietnam; and assessment of sustainability issues. In: Hoanh, C., Tuong, T., Gowing, J., Hardy, B. (Eds.) *Environment and livelihoods in tropical coastal zones. (pp.48-60)*. CABI, Wallingford, UK.

Gravinese, P. M., Enochs, I. C., Manzello, D. P., & van Woesik, R. (2018). Warming and $pCO_2$ effects on Florida stone crab larvae. *Estuarine, Coastal and Shelf Science*, 204, 193-201.

Gunakar, S., & Bhatta, R. (2021). The Role of Social Capital in the Performance of Fish Business. Economic and Political Weekly, LVI(1).

Gutiérrez, N. L., Hilborn, R., & Defeo, O. (2011). Leadership, social capital and incentives promote successful fisheries. *Nature*, 470(7334), 386–389.

Hall, D. (2003). The International Political Ecology of Industrial Shrimp Aquaculture and Industrial Plantation Forestry in Southeast Asia. *Journal of Southeast Asian Studies*, 34(2), 251-264.

Hallegraeff, G. M. (2010). Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge 1. *Journal of Phycology*, 46(2), 220-235.

Halwart, M. & Gupta, M. V. (2004). *Culture of Fish in Rice Fields*. FAO; WorldFish Center.

Hamasaki, K. (2003). Effects of temperature on the egg incubation period, survival and developmental period of larvae of the mud crab *Scylla serrata* (Forskål) (Brachyura: Portunidae) reared in the laboratory. *Aquaculture*, 219(1–4), 561–572.

Hammer, Ø., Harper, D.A.T., & Ryan, P. D. (2001). PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica* 4(1): 9pp.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162(3859), 1243–1248.

Hashem, A., Tabassum, B., & Fathi Abd_Allah, E. (2019). Bacillus subtilis: A plant-growth promoting rhizobacterium that also impacts biotic stress. *Saudi Journal of Biological Sciences*, 26(6), 1291–1297.

Herath, S.S, & Satoh, S. (2015). Environmental impact of phosphorus and nitrogen from aquaculture In Davis, D.A. (Eds) *Feed and feeding practices in aquaculture* (p. 369–386). Oxford: Woodhead Publishing.

Hernández, M., Dumont, M. G., Yuan, Q., & Conrad, R. (2015). Different bacterial populations associated with the roots and rhizosphere of rice incorporate plant-derived carbon. *Applied and Environmental Microbiology*, 81(6), 2244–2253.

Herrero, A., Muro-Pastor, A. M., & Flores, E. (2001). Nitrogen control in cyanobacteria. *Journal of Bacteriology*, 183(2), 411–425.

Hilborn, R., Fulton, E. A., Green, B. S., Hartmann, K., Tracey, S. R., & Watson, R. A. (2015). When is a fishery sustainable? *Canadian Journal of Fisheries and Aquatic Sciences*, 72(9), 1433–1441.

Hill, B. J. (1978). Activity, track and speed of movement of crab *Scylla serrata* in an estuary. *Marine Biology*, 47, 135 –141.

Hill, B. J., M. J. Williams, P. Dutton & F. Valley. (1982). Distribution of juvenile, sub-adult and adult *Scylla serrata* (Crustacea: Portunidae) on tidal flats in Australia. *Marine Biology*, 120, 117–120.

Hinkel, J., Cox, M. E., Schlüter, M., Binder, C. R., & Falk, T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*, 20(1).

Hong To, T.T., Yanagawa, H., Khanh Thuan, N., Hiep, D.M., Cuong, D.V., Khai, L.T.L., Taniguchi, T., Kubo, R. and Hayashidani, H. (2020). Prevalence of *Vibrio parahaemolyticus* Causing Acute Hepatopancreatic Necrosis Disease of Shrimp in Shrimp, Molluscan Shellfish and Water Samples in the Mekong Delta, Vietnam. *Biology*, 9(10), 312.

Hossain, M., Ut, T.T. & Bose, M.L. (2006). Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C., Tuong, T., Gowing, J., Hardy, B. (Eds.) *Environment and livelihoods in tropical coastal zones. (pp.30-47)*. CABI, Wallingford, UK.

Hugon, P., Dufour, J. C., Colson, P., Fournier, P. E., Sallah, K., & Raoult, D. (2015). A comprehensive repertoire of prokaryotic species identified in human beings. *The Lancet Infectious Diseases*, 15(10), 1211–1219.

Huntington, T.C. and Hasan, M.R. 2009. Fish as feed inputs for aquaculture – practices, sustainability and implications: a global synthesis. In M.R. Hasan and M. Halwart (Eds), *Fish as feed inputs for aquaculture: practices, sustainability and implications*. FAO Fisheries and Aquaculture Technical Paper. No. 518. Rome, FAO. pp. 1–61.

Hyland, S. J., Hill, B. J. and Lee, C. P. (1984). Movement within and between different habitats by the portunid crab *Scylla serrata*. *Marine Biology*, 80, 57–61.

Iacob, S., Iacob, D. G., & Luminos, L. M. (2019). Intestinal microbiota as a host defense mechanism to infectious threats. *Frontiers in Microbiology*, 10(JAN), 1–9.

IBEF (2020). *Agriculture and Allied Industries*. India Bran Equity Foundation, pp.39.

Ilinskaya, O. N., Ulyanova, V. V., Yarullina, D. R., & Gataullin, I. G. (2017). Secretome of Intestinal bacilli: A natural guard against pathologies. *Frontiers in Microbiology*, 8(SEP), 1–15.

Imai, H., Cheng, J.H., Hamasaki, K. and Numachi, K. I. (2004). Identification of four mud crab species (genus *Scylla*) using ITS-1 and 16S rDNA markers. *Aquatic Living Resources*, 17, 31-34.

Inglis, D. & Thorpe, C. (2012). *An invitation to social theory*. Cambridge: Polity.

IPCC (2014). *Intergovernmental Panel on Climate Change 5th Assessment Report*. IPCC, Cambridge and New York.

Islam, M. L., Siddiky, M. N. S. M., & Yahya, K. (2018). Growth, survival and intactness of green mud crab (*Scylla paramamosain*) broodstock under different captive grow out protocols. *SAARC Journal of Agriculture*, 16(1), 169-180.

ITC (2019). *International Trade Centre Trade Map*. List of importing markets for the product exported by India in 2019. Product: 030624 Crabs, even smoked, whether in shell or not, live, fresh, chilled, dried, salted or in brine, incl. crabs in shell, cooked by steaming or by boiling in water.

Jagannathan, R., Matsa, D. A., Meier, I., & Tarhan, V. (2016). Why do firms use high discount rates? *Journal of Financial Economics*, 120(3), 445–463.

Jahan, H., & Islam, M. S. (2016). Economic performance of live crab (*Scylla serrata*) business in the southwest coastal region of Bangladesh. *International Journal of Fisheries and Aquatic Studies*, 4(1), pp. 453–457.

Jayanti, A. D., Fitriya, W., Setyobudi, E., Budhiyanti, S. A., Suadi, S., & Kune, S. J. (2018). The vulnerability of fishermen's community and livelihood opportunity through drought and seasonal changes in border area of Indonesia-Timor Leste. *IOP Conference Series: Earth and Environmental Science*, 139(1).

Jentoft, S., Chuenpagdee, R. (2015). Assessing governability of small-scale fisheries. In Jentoft, S., Chuenpagdee, R. (Eds.) *Interactive governance for small-fisheries. Global Reflections (pp.17-35).* Centre for Maritime Research MARE. Springer, Cham.

Jithendran, K. P., Poornima, M., Balasubramanian, C. P., & Kulasekarapandian, S. (2010). Diseases of mud crabs (*Scylla* spp.): An overview. *Indian Journal of Fisheries*, 57(3), 55–63.

Joffre, O. M., Freed, S., Bernhardt, J., Teoh, S. J., Sambath, S., & Belton, B. (2021). Assessing the Potential for Sustainable Aquaculture Development in Cambodia. *Frontiers in Sustainable Food Systems*, 379.

Joffre, O. M., Poortvliet, P. M., & Klerkx, L. (2018). Are shrimp farmers actual gamblers? An analysis of risk perception and risk management behaviors among shrimp farmers in the Mekong Delta. *Aquaculture*, 495(April), 528–537.

Johnson, D. (2015). Giant Mud Crab. In: Stewart, J., A. Hegarty, C. Young, A. M. Fowler and J. Craig (Eds.) *Status of Fisheries Resources in NSW 2013-14.* NSW Department of Primary Industries, Mosman.

Jonah, F. E., Agbo, N. W., Agbeti, W., Adjei-Boateng, D., & Shimba, M. J. (2015). The ecological effects of beach sand mining in Ghana using ghost crabs (Ocypode species) as biological indicators. *Ocean and Coastal Management*, 112, pp.18-24.

Jones, J.L. (2014). VIBRIO | Introduction, Including Vibrio parahaemolyticus, Vibrio vulnificus, and Other Vibrio Species. In: Batt, C.A., Tortorello, M.L. (Eds.) Encyclopedia of Food Microbiology (2nd edition) (pp.691-698). Academic Press.

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences of the United States of America*, 110(6), 2076–2081.

Kathirvel, M. & Srinivasagam, S. (1992). Resource and exploitation of mud crab *Scylla serrata* (Forskal) in India. In Angell, C.A. (Eds), *Report of the seminar on mud crab culture and trade* (pp. 84-94.). Bay of Bengal Programme, Madras. BOBP/REP/51.

Kébé, M. and Muir, J. (2008). The sustainable livelihoods approach: new directions in West and Central African small-scale fisheries In: Westlund, L., Holvoet, K., Kébé, M. (Eds), *Achieving poverty reduction through responsible fisheries. Lessons from West and Central Africa*. FAO Fisheries and Aquaculture Technical Paper. No. 513. Rome, Italy.

Kébé, M., Jern, P., Collins, R., Kay, W., & Kekula, E. (2009). *A livelihoods analysis of coastal fisheries communities in Liberia*. In FAO Fisheries and Aquaculture Circular. No. 1043. Rome.

Keeling, R. F., Körtzinger, A., & Gruber, N. (2010). Ocean deoxygenation in a warming world. *Annual Review of Marine Science*, 2(1), 199–229.

Keenan C.P. (1999). Aquaculture of the mud crab, genus *Scylla*, past, present and future. In Keenan, C.P., Blackshaw, A. (Eds.), *Mud crab aquaculture and biology, proceedings of an international scientific forum, 21–24 April 1997, Darwin, Australia* (pp 9–13). ACIAR Proceedings No. 78. Canberra: Australian Centre for International Agricultural Research.

Keenan, C. P., Davie, P. J. F., & Mann, D. L. (1998). A Revision Of The Genus *Scylla* De hann, 1833 (Crustacea : Decapoda : Brachyura : Portunidae ). *The Raffles Bulletin of Zoology*, 46(1), 217–245.

Kelly, D., Yang, L., & Pei, Z. (2018). Gut Microbiota, Fusobacteria, and Colorectal Cancer. *Diseases*, 6(4), 109.

Kim, S., Covington, A., & Pamer, E. G. (2017). The intestinal microbiota: Antibiotics, colonization resistance, and enteric pathogens. *Immunological Reviews*, 279(1), 90–105.

Kincaid, H. L. (1983). Inbreeding in fish populations used for aquaculture. *Aquaculture*, 33(1–4), 215–227.

Klein, J. T., & Newell, W. H. (1996). Advancing Interdisciplinary Studies. In Gaff, J. G., Ratcliff, J. L. & Associates (Eds.), *Handbook of the Undergraduate Curriculum. A Comprehensive Guide to Purposes, Structures, Practices, and Change* (pp. 393-415). San Francisco, CA: Jossey- Bass.

Klir, G. (1972). The Polyphonic General Systems Theory. In Klir, G.J. (Ed.), *Trends in General Systems Theory*. John Wiley & Sons Inc.

Kostic, A. D., Gevers, D., Pedamallu, C. S., Michaud, M., Duke, F., Earl, A. M., Ojesina, A. I., Jung, J., Bass, A. J., Tabernero, J., Baselga, J., Liu, C., Shivdasani, R. A., Ogino, S., Birren, B. W., Huttenhower, C., Garrett, W. S., & Meyerson, M. (2012). Genomic analysis identifies association of *Fusobacterium* with colorectal carcinoma. *Genome Research*, 22(2), 292–298.

Kosuge, T. (2001). Brief assessment of stock of mud crabs *Scylla* spp. in Matang Mangrove Forest, Malaysia and proposal for resources management. *Japan Agricultural Research Quarterly*, 35(2), 145–148.

Krishna, M. N., Rao Kakara, R., Rao, G. V, & Ramesh Babu, K. (2016). Microbial assessment of commercially important crabs from Visakhapatnam fishing harbour, east coast of India. European *Journal of Experimental Biology*, 6(4), 57–61.

Krishnan, M., Salim, S.S., Narayanakumar, R., Barik, N. and Ponnusamy, K. (2014) Brackishwater Aquaculture. In Sathiadas, R., Shyam, S., Salim, S. & Narayanakumar, K. (Eds.), *Livelihood status of Fishers in India* (pp.191-244). Central Marine Fisheries Research Institute, Cochin.

Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M., & Gattuso, J. P. (2013). Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology*, 19(6), 1884–1896.

Kumar, G., & Engle, C. R. (2016). Technological Advances that Led to Growth of Shrimp, Salmon, and Tilapia Farming. *Reviews in Fisheries Science and Aquaculture*, 24(2), 136–152.

Kumar, P., Dey, M. M., & Paraguas, F. J. (2005). Demand for Fish by Species in India : Three- stage Budgeting Framework. *Agricultural Economics Research Review*, 18, 167–186.

Kummari, S., Ch, B. P., & Mamidala, S. P. (2018). Opportunities and prospects of inland freshwater aquaculture in Telangana: A step towards blue revolution. *Journal of Entomology and Zoology Studies*, 6(3), 314-319.

Kurien J. (1996). *Towards a New Agenda for Sustainable Small-Scale Fisheries Development*. SIFFS, Trivandrum.

Lalitha, K. V., & Thampuran, N. (2012). Bacterial flora of farmed mud crab, *Scylla serrata* (Forskal, 1775) and farm environments in Kerala, India. *Indian Journal of Fisheries*, 59(2), 153–160.

Landsberg, J. H. (2002). The effects of harmful algal blooms on aquatic organisms. *Reviews in Fisheries Science*, 10(2), 113–390.

Lavilla-Pitogo, C. R., & de la Peña, L. D. (2004). Diseases in farmed mud crabs *Scylla* spp.: Diagnosis, prevention, and control. Aquaculture Dept., Southeast Asian Fisheries Development Center.

Lavoie, C., Courcelle, M., Redivo, B. and Derome, N. (2018). Structural and compositional mismatch between captive and wild Atlantic salmon (*Salmo salar*) parrs' gut microbiota highlights the relevance of integrating molecular ecology for management and conservation methods. *Evol. Appl*., 11(9), 1671–1685.

Lawley, T. D., & Walker, A. W. (2013). Intestinal colonization resistance. *Immunology*, 138(1), 1–11.

Le Vay, L. (2001). Ecology and Management of Mud Crab *Scylla* spp. *Asian Fisheries Science*, 14, 101–111.

Lebata, M. J. H. L., Le Vay, L., Walton, M. E., Biñas, J. B., Quinitio, E. T., Rodriguez, E. M., & Primavera, J. H. (2009). Evaluation of hatchery-based enhancement of the mud crab, *Scylla* spp., fisheries in mangroves: Comparison of species and release strategies. *Marine and Freshwater Research*, 60(1), 58–69.

Lebata, Ma. J.H.L., Le Vay, L., Primavera, J.H Walton, M.E. & Binas, J.N. (2007). Baseline assessment of fisheries for three species of mud crabs (*Scylla* spp.) in the mangroves of Ibajay, Aklan, Philippines. *Bulletin of Marine Science*, 80(3), 891-904.

Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., Erisman, B. E., Finkbeiner, E., Hinojosa-Arango, G., Moreno-Báez, M., Nagavarapu, S., Reddy, S. M. W., Sánchez-Rodríguez, A., Siegel, K., Ulibarria-Valenzuela, J. J., Weaver, A. H., & Aburto-Oropeza, O.

(2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 112(19), 5979–5984. *Ecology and Society*, 18(4), 26.

Li Y. F., Yang N., Liang X., Yoshida A., Osatomi K., Power D. M., *et al.* (2018). Elevated Seawater temperatures decrease microbial diversity in the gut of *Mytilus coruscus*. Front. Physiol. 9:839.

Li, K., Guan, W., Wei, G., Liu, B., Xu, J., Zhao, L., & Zhang, Y. (2007). Phylogenetic analysis of intestinal bacteria in the Chinese mitten crab (*Eriocheir sinensis*). *Journal of Applied Microbiology*, 103(3), 675–682.

Li, S., Sun, L., Wu, H., Hu, Z., Liu, W., Li, Y., & Wen, X. (2012). The intestinal microbial diversity in mud crab (*Scylla paramamosain*) as determined by PCR-DGGE and clone library analysis. *Journal of Applied Microbiology*, 113(6), 1341–1351.

Li, Y. Y., Xia, X. A., Wu, Q. Y., Liu, W. H. and Lin, Y.S. (2008). Infection with *Hematodinium* sp. in mud crabs *Scylla serrata* cultured in low salinity water in southern China. *Diseases of Aquatic Organisms*, 20;82(2):145-50.

Lindner, B. (2005). *Impacts of mud crab hatchery technology in Vietnam ACIAR projects FIS / 1992 / 017 and FIS / 1999 / 076.* ACIAR Projects FIS/1992/017 and FIS/1999/076, October, 60.

Lingam, L. (1994). Women-headed households. Coping with caste, class and gender hierarchies. *Economic and Political Weekly*, 29(12), 699-704.

Little, D. C., Barman, B. K., Belton, B., Beveridge, M. C., Bush, S. J., Dabaddie, L., Demaine, H., Edwards, P., Haque, M. M., Kibria, G., Morales, E., Murray, F. J., Leschen, W. a, Nandeesha, M. C., & Sukadi, F. (2010). Alleviating poverty through aquaculture: progress, opportunities and improvements. Farming the Waters for People and Food. *Proceedings of the Global Conference on Aquaculture,* 1, 719–783.

Liu, H., Guo, X., Gooneratne, R., Lai, R., Zeng, C., Zhan, F., & Wang, W. (2016). The gut microbiome and degradation enzyme activity of wild freshwater fishes influenced by their trophic levels. *Scientific Reports*, 6, 1–12.

Liu, Z. M., Wang, G. Z., Wu, L. S., Zeng, Z. S., & Chen, X. L. (2013). Seasonal change in mitochondrial function and metabolic enzyme activity of different populations of the mud crab, Scylla paramamosain, from China. *Aquaculture*, 376, 68-75.

Llewellyn, M. S., Boutin, S., Hoseinifar, S. H., & Derome, N. (2014). Teleost microbiomes: The state of the art in their characterization, manipulation and importance in aquaculture and fisheries. *Frontiers in Microbiology*, 5(JUN), 1–1.

Lozán, J. L. (2000). On the threat to the European crayfish: A contribution with the study of the activity behaviour of four crayfish species (Decapoda: Astacidae). *Limnologica*, 30(2), 156–161.

Lucu, Č., & Towle, D. W. (2003). Na++ K+-ATPase in gills of aquatic crustacea. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 135(2), 195-214.

Lynch, J., Cain, M., Frame, D., & Pierrehumbert, R. (2021). Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO2-emitting sectors. *Frontiers in sustainable food systems*, 4, 300.

Ma, L. B., Zhang, F. Y., Ma, C. Y., & Qiao, Z. G. (2006). *Scylla* paramamosain (Estampador) the most common mud crab (Genus *Scylla*) in China: Evidence from mtDNA. *Aquaculture Research*, 37(16), 1694–1698.

Ma, Q., Ma, H., Chen, J., Ma, C., Feng, N., Xu, Z., Li, S., Jiang, W., Qiao, Z., & Ma, L. (2013). Parentage assignment of the mud crab (*Scylla paramamosain*) based on microsatellite markers. *Biochemical Systematics and Ecology*, 49, 62–68.

Malham, S. K., Rajko-Nenow, P., Howlett, E., Tuson, K. E., Perkins, T. L., Pallett, D. W., Wang, H., Jago, C. F., Jones, D. L., & McDonald, J. E. (2014). The interaction of human microbial pathogens, particulate material and nutrients in estuarine environments and their impacts on recreational and shellfish waters. *Environmental Sciences: Processes and Impa*cts, 16(9), 2145–2155.

Mann, D. L., Asakawa, T., Kelly, B., Lindsay, T., & Paterson, B. (2007). Stocking density and artificial habitat influence stock structure and yield from intensive nursery systems for mud crabs *Scylla serrata* (Forsskål 1775). *Aquaculture Research*, 38(14), 1580-1587.

Marichamy, R., & Rajapackiam, S. (2001). The Aquaculture of *Scylla* Species in India. *Asian Fisheries Science*, 14, 231–238.

Martinez-Urtaza, J., Bowers, J. C., Trinanes, J., & DePaola, A. (2010). Climate anomalies and the increasing risk of *Vibrio parahaemolyticus* and *Vibrio vulnificus* illnesses. *Food Research International*, 43(7), 1780–1790.

Martins, I. M., & Gasalla, M. A. (2020). Adaptive Capacity Level Shapes Social Vulnerability to Climate Change of Fishing Communities in the South Brazil Bight. *Frontiers in Marine Science*, 7(July), 1–11.

Martins, I. M., Medeiros, R. P., Di Domenico, M., & Hanazaki, N. (2018). What fishers' local ecological knowledge can reveal about the changes in exploited fish catches. *Fisheries Research*, 198(October 2017), 109–116.

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, 19(2).

Md Zoqratt, M. Z. H., Eng, W. W. H., Thai, B. T., Austin, C. M., & Gan, H. M. (2018). Microbiome analysis of Pacific white shrimp gut and rearing water from Malaysia and Vietnam: implications for aquaculture research and management. *PeerJ*, 6, e5826.

Meadows, D. H. (2008). *Thinking in Systems: A Primer*. London: Earthscan.

Mikulcak, F., Haider, J.L., Abson, D.J., Newig, J. & Fischer, J. (2015). Applying a capitals approach to understand rural development traps: A case study from post-socialist Romania. *Land Use Policy*, 43, 248–258.

Milici, M., Tomasch, J., Wos-Oxley, M. L., Wang, H., Jáuregui, R., Camarinha-Silva, A., Deng, Z. L., Plumeier, I., Giebel, H. A., Wurst, M., Pieper, D. H., Simon, M. and Wagner-Döbler, I. (2016). Low diversity of planktonic bacteria in the tropical ocean. Scientific reports, 6, 19054.

Ministry of Information and Broadcasting (2018). *India 2018: A Reference Annual.* Publications Division Ministry of Information & Broadcasting, Government of India.

Ministry of Social Justice and Empowerment (2017). *Scheduled Caste Welfare*. Available at: http://socialjustice.nic.in/UserView/index?mid=19536 (Accessed 18 July 2018).

Mirera, D & Moksnes, P.O. (2013). Cannibalistic interactions of juvenile mud crabs Scylla serrata: the effect of shelter and crab size. *African Journal of Marine Science*, 35(4).

Mirera, D. & Moksnes, P.O. (2014). Comparative performance of wild juvenile mud crab (*Scylla serrata*) in different culture systems in East Africa: effect of shelter, crab size and stocking density. *Aquaculture International,* 23(1), 155-173.

Mirera, D. O., Ochiewo, J. & Munyi, F. (2014). Social and economic implications of small-scale mud crab (*Scylla serrata*) aquaculture: The case of organised community groups. *Aquaculture International*, 22(4), 1499–1514.

Mirera, D. O., Ochiewo, J., Munyi, F., & Muriuki, T. (2013). Heredity or traditional knowledge: Fishing tactics and dynamics of artisanal mangrove crab (*Scylla serrata*) fishery. *Ocean and Coastal Management*, 84, 119–129.

Mirera, O. D. (2011). Trends in exploitation, development and management of artisanal mud crab (*Scylla serrata*-Forsskal-1775) fishery and small-scale culture in Kenya: An overview. *Ocean and Coastal Management*, 54(11), 844–855.

Moksnes, P., Mirera, D., Lokina, R., Ochiewo, J., Mahudi, H., Jiddawi, N., Hamad, M. &Troell, M. (2015a). Feasibility of extensive, small-scale mud crab (*Scylla serrata*) farming in East Africa. *WIO Journal of Marine Science*, 14, 23-38.

Moksnes, P.O., Mirera, D.O., Bjorkvik, E., Hamad, M.I., Mahudi, H.M., Nyqvist, D., Jiddawi, N. & Troell, M. (2015b). Stepwise function of natural growth for *Scylla serrata* in East Africa: A valuable tool for assessing growth of mud crabs in aquaculture. *Aquaculture Research*, 46(12), 2938–2953.

Moloney, R.D., Desbonnet, L., Clarke, G., Dinan, T.G. and Cryan, J.F. (2014). The microbiome: stress, health and disease. *Mammalian Genome,* 25, 49-74.

Moore, M. A., Boardman, A. E., Vining, A. R., Weimer, D. L., & Greenberg, D. H. (2004). “Just give me a number!” Practical values for the social discount rate. *Journal of Policy Analysis and Management*, 23(4), 789–812.

Morse, S., & McNamara, N. (2013). *Sustainable livelihood approach: A critique of theory and practice*. Springer Netherlands.

Motoh, H., de la Pena, D., & Tampos, E. (1977). Laboratory breeding of the mud crab *Scylla serrata* (Forskal ) through the zoea and megalopa stages to the crab stage. *SEAFDEC Aquaculture Department Quarterly Research Report*, 1(4), 14–18.

Mulokozi, D. P., Mmanda, F. P., Onyango, P., Lundh, T., Tamatamah, R., & Berg, H. (2020). Rural aquaculture: Assessment of its contribution to household income and farmers’ perception in selected districts, Tanzania. *Aquaculture Economics and Management*, 0(0), 1–19.

Mwaluma, J. M., & Kaunda-Arara, B. (2021). Growth and survival of Mud Crab, *Scylla serrata*, reared in bottom and floating cages within Mida Creek mangroves, coastal Kenya. *Aquatic Ecosystem Health & Management*, 24(1), 27-34.

Namonje-Kapembwa, T., & Samboko, P. (2020). Is aquaculture production by small-scale farmers profitable in Zambia? *International Journal of Fisheries and Aquaculture*, 12(1), 6–20.

Nayak, P. K. (2014). The chilika lagoon social-ecological system: An historical analysis. *Ecology and Society*, 19(1).

Nayak, P. K. (2017). Fisher communities in transition: understanding change from a livelihood perspective in Chilika Lagoon, India. *Maritime Studies*, 16(1).

Nayak, P. K., & Berkes, F. (2010). Whose marginalisation? Politics around environmental injustices in India's Chilika lagoon. *Local Environment*, 15(6), 553–567.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D.C., Lubchenco, J, Shumway, S.E. & Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, 591(7851), 551-563.

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, 10(3).

Newell, W. H. (2001). A Theory of Interdisciplinary Studies. Issues in Integrative Studies, 19(1), 1–25.

Nghia, T. T., Wille, M., Binh, T. C., Thanh, H. P., Van Danh, N., & Sorgeloos, P. (2007). Improved techniques for rearing mud crab *Scylla paramamosain* (Estampador 1949) larvae. *Aquaculture Research*, 38(14), 1539–1553.

NSSO (2016). *Livestock Ownership in India. NSS 70th round, January – December 2013*. Report No. 572(70/18.1/2). National Sample Survey Office, New Delhi.

Nurdiani, R., & Zeng, C. (2007). Effects of temperature and salinity on the survival and development of mud crab, *Scylla serrata* (Forsskål), larvae. Aquaculture Research, 38(14), 1529-1538.

OECD (1993). *Glossary of Industrial Organisation Economics and Competition Law.* Directorate for Financial, Fiscal and Enterprise Affairs, OECD.

Ogawa, C. Y., Hamasaki, K., Dan, S., Obata, Y., & Kitada, S. (2012). Species composition, reproduction, and body size of mud crabs, *Scylla* spp., caught in Urado Bay, Japan. *Journal of Crustacean Biology*, 32(5), 762–768.

Okolodkov, Y. B. (2005). The global distributional patterns of toxic, bloom dinoflagellates recorded from the Eurasian Arctic. *Harmful Algae*, 4(2), 351–369.

Oksanen, J., Blanchet, G. F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs E. & Wagner, H. (2017). vegan: Community Ecology Package. R package version 2.4-3. https://CRAN.R-project.org/package=vegan

Ooi, M. C., Goulden, E. F., Smith, G. G., Nowak, B. F., & Bridle, A. R. (2017). Developmental and gut-related changes to microbiomes of the cultured juvenile spiny lobster *Panulirus ornatus. FEMS Microbiology Ecology*, 93(12), 1–10.

Oppenheimer, M., Glavovic ,B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto ,R.M. *et al.* (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Orchard, S. E., Stringer, L. C., & Quinn, C. H. (2015). Impacts of aquaculture on social networks in the mangrove systems of northern Vietnam. *Ocean and Coastal Management*, 114, 1–10.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action.* Cambridge university press.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *PNAS*, 104(39), 15181–15187.

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, 325(5939), 419–422.

Páez-Osuna, F. (2001). The environmental impact of shrimp aquaculture: Causes, effects, and mitigating alternatives. *Environmental Management*, 28(1), 131–140.

Paital, B., & Chainy, G. B. N. (2010). Antioxidant defenses and oxidative stress parameters in tissues of mud crab (*Scylla serrata*) with reference to changing salinity. *Comparative Biochemistry and Physiology - C Toxicology and Pharmacology*, 151(1), 142–151.

Paital, B., & Chainy, G. B. N. (2014). Effects of temperature on complexes I and II mediated respiration, ROS generation and oxidative stress status in isolated gill mitochondria of the mud crab *Scylla serrata*. *Journal of Thermal Biology*, 41(1), 104–111.

Pansch, C., Nasrolahi, A., Appelhans, Y. S., & Wahl, M. (2012). Impacts of ocean warming and acidification on the larval development of the barnacle *Amphibalanus improvisus*. *Journal of Experimental Marine Biology and Ecology*, 420, 48-55.

Partelow, S., & Boda, C. (2015). A modified diagnostic social-ecological system framework for lobster fisheries: Case implementation and sustainability assessment in Southern California. *Ocean and Coastal Management*, 114, 204–217.

Pascoe, E. L., Hauffe, H. C., Marchesi, J. R., & Perkins, S. E. (2017). Network analysis of gut microbiota literature: an overview of the research landscape in non-human animal studies. *The ISME journal*, 11(12), 2644-2651.

Paytuvi, A., Battista, E., Scippacercola, F., Sundesha, V., R, A. C., & Sanseverino, W. (2017). Gaia: an Integrated Metagenomics Suite. *bioRxiv*, 804690.

Pendleton, L., Comte, A., Langdon, C., Ekstrom, J. A., Cooley, S. R., Suatoni, L., Beck, M. W., Brander, L. M., Burke, L., Cinner, J. E., Doherty, C., Edwards, P. E. T., Gledhill, D., Jiang, L. Q., Van Hooidonk, R. J., Teh, L., Waldbusser, G. G., & Ritter, J. (2016). Coral reefs and people in a high-CO2 world: Where can science make a difference to people? *PLoS ONE*, 11(11), 1–21.

Pickard, J. M., Zeng, M. Y., Caruso, R., & Núñez, G. (2017). Gut microbiota: Role in pathogen colonization, immune responses, and inflammatory disease. *Immunological Reviews*, 279(1), 70–89.

Pillai, B. R., & Diwan, A. D. (2002). Effects of acute salinity stress on oxygen consumption and ammonia excretion rates of the marine shrimp Metapenaeus monoceros. *Journal of Crustacean Biology*, 22(1), 45-52.

Pittman, S. J., & McAlpine, C. A. (2003). Movements of marine fish and decapod crustaceans: Process, theory and application. *Advances in Marine Biology*, 44, 205-294.

Poornima, M., Singaravel, R., Rajan, S. J. ., Ramakrishnan, S., Alavandi, S. ., & Kalaimani, N. (2012). *Vibrio harveyi* Infection in Mud Crabs (*Scylla tranquebarica*) Infected With White Spot Syndrome Virus. *International Journal of Research in Biological Sciences Universal Research Publications*, 1(3), 81–93.

Prasad, P. N. & Neelakantan, B. (1989). Maturity and Breeding of the mud crab, *Scylla serrata* (Forskal)(Decapoda: Brachyura: Portunidae). *Proceedings of the Indian Academy of Science*, 98, 341–349.

Preena, P. G., Swaminathan, T. R., Kumar, V. J. R., & Singh, I. S. B. (2020). *Antimicrobial resistance in aquaculture: a crisis for concern*. Biologia, 75(9), 1497-1517.

Pretty, J., & Ward, H. (2001). Social Capital and the Environment. *World Development*, 29(2), 209–22.

Primavera, J. H. (2006). Overcoming the impacts of aquaculture on the coastal zone. *Ocean and Coastal Management*, 49(9–10), 531–545.

Primavera, Jurgenne H., Binas, J. B., Samonte-Tan, G. P. B., Lebata, M. J. J., Alava, V. R., Walton, M., & LeVay, L. (2010). Mud crab pen culture: Replacement of fish feed requirement and impacts on mangrove community structure. *Aquaculture Research*, 41(8), 1211–1220.

Purvis, B., Mao, Y., & Robinson, D. (2018). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, 5.

Putnam, R.D. (2001). Social Capital: Measurement and Consequences. *Isuma: Canadian Journal of Policy Research*, 2, 41-51.

Quinet, E., Baumstark, L., Bonnet, J., Croq, A., Ducos, G., Meunier, D., Rigard-Cerison, A., & Roquigny, Q. (2013). *L'évaluation socioéconomique des investissements publics.*

Quinitio, E. T., Parado-Estepa, F. D., & Coloso, R. M. (2017). *Philippines: In the forefront of the mud crab industry: Proceedings of the 1st National Mud Crab Congress*. Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center.

Quinitio, E. T., Parado-Estepa, F. D., Millamena, O. M., Rodriguez, E., & Borlongan, E. (2001). Seed Production of Mud Crab *Scylla serrata* Juveniles. *Asian Fisheries Science*, 14, 161–174.

Rahi, M. L., Ferdusy, T., Wali Ahmed, S., Khan, M. N., Aziz, D., & Salin, K. R. (2020). Impact of salinity changes on growth, oxygen consumption and expression pattern of selected candidate genes in the orange mud crab (*Scylla olivacea*). *Aquaculture Research*, 51(10), 4290–4301.

Rajeish, M., Shekar, M., Madhushree, H. N., & Venugopal, M. N. (2016). Presumptive case of ciguatera fish poisoning in Mangalore, India. *Current Science*, 111(9), 1543–1547.

Rajendran, K. V, Vijayan, K. ., Santiago, T. C., & Krol, R. M. (1999). Experimental host range and histopathology of white spot syndrome virus (WSSV) infection in shrimp, prawns, crabs and lobsters from India. *Journal of Fish Diseases*, 22, 183–191.

Ramachandra, T.V., Subash Chandran, M.D., Joshi, N.V., Bhat, M., Mesta, P.N. & Naik, S. (2013). E*stuarine Fish Diversity and Livelihoods in Uttara Kannada District, Karnataka State.* Sahyadri Consevation Series 34, ENVIS Technical Report 64, CES, Indian Institute of Science, Bangalore, India.

Rameshkumar, G., Ravichandran, S., Chandrasekar, & Ajithkumar, T. (2009). Gut microbiota of crabs from the Vellar estuary, southeast coast of India. *Microbial Ecology in Health and Disease,* 21(3–4), 178–182.

Ramirez, C. and Romero, J. (2017). Fine Flounder (Paralichthys adspersus) Microbiome Showed Important Differences between Wild and Reared Specimens. *Frontiers in Microbiology*, 8:271.

Ranasinghe, R. (2020). On the need for a new generation of coastal change models for the 21st century. *Scientific reports*, 10(1), 1-6.

Rangarajan, C. (2008). *A report of the committee on social inclusion*. State Level Bankers' Committee.

Ranjan, G. (2011) 'Ethnography of Development: Challenges and Promises', *The NEHU Journal*, IX(2), pp. 50–62Rawal, V. (2008). Ownership holdings of land in rural India: Putting the record straight. *Economic and Political Weekly*, 43(10), 43–47.

Reddy, S. M. W., Wentz, A., Aburto-oropeza, O., Maxey, M., Nagavarapu, S., & Leslie, H. M. (2013). Evidence of market-driven size-selective fishing and the mediating effects of biological and institutional factors Sheila. *Ecol Appl*., 23(4), 726–741.

Reid, G. K., Gurney-Smith, H. J., Flaherty, M., Garber, A. F., Forster, I., Brewer-Dalton, K., Knowler, D., Marcogliese, D.J., Chopin, T., Moccia, R.D., Smith, C.T. & De Silva, S. (2019). Climate change and aquaculture: considering adaptation potential. *Aquaculture Environment Interactions*, 11, 603-624.

Rekha, P. (2009). Designing and construction of hatchery, ponds, pens and cages for mud crab farming In: *Training Manual on Mud Crab Breeding and Culture*. Special Publication No.45. Central Institute of Brackishwater Aquaculture, Chennai.

Richardson, R. & Suvedi, M. (2018). Assessing the Potential for Small-Scale Aquaculture in Cambodia. *Environments*, 5(7).

Robins, P. E., Skov, M. W., Lewis, M. J., Giménez, L., Davies, A. G., Malham, S. K., Neill, S. P., McDonald, J. E., Whitton, T. A., Jackson, S. E., & Jago, C. F. (2016). Impact of climate change on UK estuaries: A review of past trends and potential projections. *Estuarine, Coastal and Shelf Science*, 169, 119–135.

Robinson, J. P. W., Robinson, J., Gerry, C., Govinden, R., Freshwater, C., & Graham, N. A. J. (2020). Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. *Science Advances*, 6(8), 1–10.

Robinson, Marguerite S. (2001). *The Microfinance Revolution: Sustainable Finance for the Poor*. Washington, D.C.: World Bank.

Romano, N., & Zeng, C. (2013). Toxic Effects of Ammonia, Nitrite, and Nitrate to Decapod Crustaceans: A Review on Factors Influencing their Toxicity, Physiological Consequences, and Coping Mechanisms. *Reviews in Fisheries Science*, 21(1), 1–21.

Romano, N., Wu, X., Zeng, C., Genodepa, J., & Elliman, J. (2014). Growth, osmoregulatory responses and changes to the lipid and fatty acid composition of organs from the mud crab, *Scylla serrata*, over a broad salinity range. *Marine Biology Research*, 10(5), 460–471.

Rouf, M. A., Shahriar, S. I. M., Sarower, M. G., & Ahsan, M. N. (2016). Taxonomic clarification of mud crab species of genus *Scylla* (Brachyura: Portunidae) available in the coastal regions of Bangladesh. *Asian Fisheries Science*, 29(3), 124–136.

Rowland, I., Gibson, G., Heinken, A., Scott, K., Swann, J., Thiele, I., & Tuohy, K. (2018). Gut microbiota functions: metabolism of nutrients and other food components. *European Journal of Nutrition*, 57(1), 1–24.

Rungrassamee, W., Klanchui, A., Chaiyapechara, S., Maibunkaew, S., Tangphatsornruang, S., Jiravanichpaisal, P., & Karoonuthaisiri, N. (2013).

Bacterial Population in Intestines of the Black Tiger Shrimp (*Penaeus monodon*) under Different Growth Stages. *PLoS ONE*, 8(4).

Rungrassamee, W., Klanchui, A., Maibunkaew, S., Chaiyapechara, S., Jiravanichpaisal, P., & Karoonuthaisiri, N. (2014). Characterization of intestinal bacteria in wild and domesticated adult black tiger shrimp (*Penaeus monodon*). *PLoS ONE*, 9(3).

Ruscoe, I. M., Shelley, C. C., & Williams, G. R. (2004). The combined effects of temperature and salinity on growth and survival of juvenile mud crabs (*Scylla serrata* Forskal). *Aquaculture*, 238(1–4), 239–247.

Saito, K., Koido, S., Odamaki, T., Kajihara, M., Kato, K., Horiuchi, S., Adachi, S., Arakawa, H., Yoshida, S., Akasu, T., Ito, Z., Uchiyama, K., Saruta, M., Xiao, J. zhong, Sato, N., & Ohkusa, T. (2019). Metagenomic analyses of the gut microbiota associated with colorectal adenoma. *PLoS ONE*, 14(2), 1–18.

Salas-Leiva, J., Opazo, R., Remond, C., Uribe, E., Velez, A. & Romero, J. (2017). Characterization of the intestinal microbiota of wild-caught and farmed fine flounder (*Paralichthys adspersus*). *Lat. Am. J. Aquat. Res*., 45(2), 370-378.

Samonte, G. P. B., & Agbayani, R. F. (1992). Pond culture of mud crab (*Scylla serrata*): An economic analysis. *SEAFDEC Asian Aquaculture*, 14(4), 225-234.

Sandve, S. R., Angell, I. L., Vik, J. O., Pope, P. B., Snipen, L.-G., & Rudi, K. (2017). Stable Core Gut Microbiota across the Freshwater-to-Saltwater Transition for Farmed Atlantic Salmon. *Applied and Environmental Microbiology*, 84(2), 1–9.

Sangthong, P., & Jondeung, A. (2006). Classification of three crab morphs in the genus *Scylla* using morphometric analysis. *Kasetsart Journal - Natural Science*, 40(4), 958–970.

Sarower, M. G., Shahriar, S. I. M., Nakamura, H., Rouf, M. A., & Okada, S. (2017). Taxonomic confirmation of mud crab species (genus *Scylla*) in Bangladesh by nuclear and mitochondrial DNA markers. *Mitochondrial DNA Part A: DNA Mapping, Sequencing, and Analysis*, 28(6), 935–940.

Sathiadhas, R., & Najmudeen, T. M. (2004). Economic evaluation of mud crab farming under different production systems in India. *Aquaculture Economics & Management*, 8(1–2), 99–110.

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H. & Jinks, C. (2018). Saturation in qualitative research: exploring its conceptualization and operationalization. *Qual Quant,* 52 (4), 1893-1907.

Scanes, E., Scanes, P. R., & Ross, P. M. (2020). Climate change rapidly warms and acidifies Australian estuaries. *Nature Communications*, 11(1), 1–11.

Schmidt, V., Gomez-Chiarri, M., Roy, C., Smith, K., & Amaral-Zettler, L. (2017). Subtle Microbiome Manipulation Using Probiotics Reduces Antibiotic-Associated Mortality in Fish. *American Society for Microbiology*, 2(6), 1–13.

Scoones, I. (1998). *Sustainable rural livelihoods: A framework for analysis*. IDS Working Paper. No.72. Brighton: IDS.

Semenza, J. C., Trinanes, J., Lohr, W., Sudre, B., Löfdahl, M., Martinez-Urtaza, J., Nichols, G. L., & Rocklöv, J. (2017). Environmental suitability of *vibrio* infections in a warming climate: An early warning system. *Environmental Health Perspectives*, 125(10), 1–12.

Sen, A. (1997). Editorial: Human capital and human capability. *World Development*, 25(12), 1959–1961.

Sen, S., & Homechaudhuri, S. (2017). Population characteristics and trends in artisanal fishery of *Scylla serrata* (Forsskål, 1775) in Indian Sundarban: Implications on future managements. *Ocean and Coastal Management*, 143, 105–114.

Sengupta, A. (2017). Maharashtra to set up India's 2nd crab hatchery among mangroves in Sindhudurg. Hindustan Times (April 16) Available at: https://www.hindustantimes.com/mumbai-news/maharashtra-to-set-up-india-s-2nd-crab-hatchery-among-mangroves-in-sindhudurg/story-cvXUsJsNmDFelSXDIbvTLO.html. (Accessed on 15 December 2020).

Serene R. (1952). Les especes du genere *Scylla* a Nhatrang (Vietnam). *Proc Indo-Pacific Fish Council*, 3,133–137.

Shanthi, B. (2009). Mud crab farming as a tool to uplift the economic status of brackishwater farmers. In *Training Manual on Mud Crab Breeding and Culture*. Special Publication No.45. Central Institute of Brackishwater Aquaculture, Chennai.

Sheeba, S., (2009). Biotic environment and sand mining - a case study from Ithikkara river, south west coast of India. *Jr. of Industrial Pollution Control*, 25(2), 133-138.

Shelley, C. (2008). Capture-based aquaculture of mud crabs (*Scylla* spp.). In Lovatelli, A. and Holthus P.F. (Eds), *Capture-based aquaculture. Global overview* (pp. 255–269). FAO Fisheries Technical Paper. No. 508. Rome.

Shelley, C. and Lovatelli, A. 2011. *Mud crab aquaculture. A practical manual*. FAO Fisheries and Aquaculture Technical Paper 567. Rome, Italy.

Shepherd, C. J., & Jackson, A. J. (2013). Global fishmeal and fish-oil supply: inputs, outputs and markets. *Journal of Fish Biology*, 83(4), 1046-1066.

Shi, C., Xia, M., Li, R., Mu, C., Zhang, L., Liu, L., Ye, Y., & Wang, C. (2019). *Vibrio alginolyticus* infection induces coupled changes of bacterial community and metabolic phenotype in the gut of swimming crab. *Aquaculture*, 499, 251–259.

Shields, J. D. (2019). Climate change enhances disease processes in crustaceans: case studies in lobsters, crabs, and shrimps. *The Journal of Crustacean Biology*, 39(6), 673-683.

Shipton, T. and Hecht, T. (2007). *Coastal mariculture assessment mission final report*. Regional Programme for the Sustainable Management of the Coastal Zones of the Indian Ocean Countries (ReCoMaP), Victoria, Seychelles.

Shock, B. C., Foran, C. M., & Stueckle, T. A. (2009). Effects of salinity stress on survival, metabolism, limb regeneration, and ecdysis in *Uca pugnax*. *Journal of Crustacean Biology*, 29(3), 293–301.

Shruthi, M. S., Sushanth, V. R., & Rajashekhar, M. (2011). Diatoms as indicators of water quality deterioration in the estuaries of Dakshina Kannada and Udupi Districts of Karnataka. International *Journal of Environmental Sciences*, 2(2), 996–1006.

Siegenfeld, A. F., & Bar-Yam, Y. (2020). An Introduction to Complex Systems Science and its Applications. Complexity, ID 6105872.

Singh, A. K. (2021). State of aquatic invasive species in tropical India: An overview. *Aquatic Ecosystem Health & Management*, 24(2), 13-23.

Solomon, S., Plattner, G. K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the national academy of sciences*, 106(6), 1704-1709.

Somboonna, N., Mangkalanan, S., Udompetcharaporn, A., Krittanai, C., Sritunyalucksana, K., & Flegel, T. W. (2010). Mud crab susceptibility to disease from white spot syndrome virus is species-dependent. *BMC Research Notes*, 3(1), 315.

Son, H. H. (2012). *On Measuring Human Capital: A Case Study of Viet Nam*. ADB Economics Working Paper Series No. 311. Asian Development Bank, Philippines.

Song, A. M., Bodwitch, H., & Scholtens, J. (2018a). Why marginality persists in a governable fishery—the case of New Zealand. *Maritime Studies*, 17(3), 285–293.

Song, X., Tao, B., Guo, J., Li, J., & Chen, G. (2018b). Changes in the microbial community structure and soil chemical properties of vertisols under different cropping systems in northern China. *Frontiers in Environmental Science*, 6, 1–14.

Spanopoulos-Hernández, M., Martínez-Palacios, C. A., Vanegas-Pérez, R. C., Rosas, C., & Ross, L. G. (2005). The combined effects of salinity and temperature on the oxygen consumption of juvenile shrimps Litopenaeus stylirostris (Stimpson, 1874). *Aquaculture*, 244(1-4), 341-348.

Srivastav, R., & Suneja, G. (2019). Recent Advances in Microbial Genome Sequencing. In Tripathi, V. *et al.* (Eds.) *Microbial Genomics in Sustainable Agroecosystems* (pp.131-144). Springer Nature, Singapore.

Statham, P. J. (2012). Nutrients in estuaries - An overview and the potential impacts of climate change. *Science of the Total Environment*, 434, 213–227.

Stephenson, W. (1960). The Australian portunids (Crustacea: Portunidae). *Marine and Freshwater Research,* 12(1), 92–128.

Sterman, J. D. (2012). Sustaining sustainability: creating a systems science in a fragmented academy and polarized world. In Weinstein, M.P. and Turner, R.E. (Eds.) *Sustainability Science: The Emerging Paradigm and the Urban Environment* (pp. 21-58). Springer, New York, NY.

Su, Y.C. & Liu, C. (2007). *Vibrio parahaemolyticus*: a concern of seafood safety. *Food Microbiology*, 24(6), 549-558.

Subash Chandran, M.D., Mesta, P., Boominathan, M., Rao, G.R. & Ramachandra, T.V. (2012). *Aghanashini estuary in Kumta taluk, Uttara Kannada – biological heritage site*. ENVIS Technical Report: 35.

Subramanyam, L. M., & Prasad, R. S. (2017). Growth and Development of Aquaculture in Andhra Pradesh- A Study. International Journal of Academic Research, 4(8).

Sugiura, S. H. (2018). Phosphorus, aquaculture, and the environment. *Reviews in Fisheries Science & Aquaculture*, 26(4), 515-521.

Sulkin, S., Hinz, S., & Rodriguez, M. (2003). Effects of exposure to toxic and non-toxic dinoflagellates on oxygen consumption and locomotion in stage 1 larvae of the crabs Cancer oregonensis and C. magister. *Marine Biology*, 142(2), 205–211.

Sullam, K. E., Essinger, S. D., Lozupone, C. A., O'Connor, M. P., Rosen, G. L., Knight, R., Kilham, S. S., & Russell, J. A. (2012). Environmental and ecological factors that shape the gut bacterial communities of fish: A meta-analysis. *Molecular Ecology*, 21(13), 3363–3378.

Sullivan, T. J., & Neigel, J. E. (2018). Effects of temperature and salinity on prevalence and intensity of infection of blue crabs, Callinectes sapidus, by *Vibrio cholerae, V. parahaemolyticus,* and *V. vulnificus* in Louisiana. *Journal of Invertebrate Pathology*, 15, 82–90.

Sulochanan, B. (2003). Mangrove ecosystem and its impact on fisheries. CMFRI. [Online] Available at: http://eprints.cmfri.org.in/9873/1/Bindu_10.pdf (Accessed 15 February 2018).

Supamattaya, K., Hoffmann, R. W., Boonyaratpalin, S., & Kanchnaphum, P. (1998). Experimental transmission of white spot syndrome virus (WSSV) from black tiger shrimp Penaeus monodon to the sand crab Portunus pelagicus, mud crab *Scylla serrata* and krill Acetes sp. *Disease of Aquatic Organisms*, 32, 79–85.

Tacon, A.G.J. &Metian, M. (2013). Fish Matters: Importance of Aquatic Foods in Human Nutrition and Global Food Supply. *Reviews in Fisheries Science*, 21 (1), 22-38.

Talpur, A. D., Memon, A. J., Khan, M. I., Ikhwanuddin, M., Danish Daniel, M. M., & Abol-Munafi, A. B. (2011). A novel of gut pathogenic bacteria of blue swimming crab *Portunus pelagicus* (Linneaus, 1758) and pathogenicity of *Vibrio harveyi* a transmission agent in larval culture under hatchery conditions. *Research Journal of Applied Sciences*, 6(2), 116–127.

Tang, K. F. J., & Bondad-Reantaso, M. G. (2019). Impacts of acute hepatopancreatic necrosis disease on commercial shrimp aquaculture.

*Revue Scientifique et Technique (International Office of Epizootics)*, 38(2), 477–490.

Tappin, A. D. (2002). An examination of the fluxes of nitrogen and phosphorus in temperate and tropical estuaries: Current estimates and uncertainties. *Estuarine, Coastal and Shelf Science*, 55(6), 885–901.

Tarnecki, A. M., Wafapoor, M., Phillips, R. N., & Rhody, N. R. (2019). Benefits of a Bacillus probiotic to larval fish survival and transport stress resistance. *Scientific Reports*, 9(1), 1–11.

Teh, L. C. L., & Pauly, D. (2018). Who brings in the fish? The relative contribution of small-scale and industrial fisheries to food security in Southeast Asia. *Frontiers in Marine Science*, 4, 1–9.

Thampi Samraj, Y. C., Mandal, A., Kumaran, G., Sethuramalingam, A., Srinivasan, P. and Kumar, J., 2015. Status of mud crab industry in India. In E. T. Quinitio, F. D. Parado-Estepa, Y. C. Thampi Sam Raj, & A. Mandal (Eds.), Proceedings of the International Seminar-Workshop on Mud Crab Aquaculture and Fisheries Management, 10-12 April 2013, Tamil Nadu, India (pp. 17-26). Tamil Nadu, India: Rajiv Gandhi Centre for Aquaculture (MPEDA).

The Coastal Aquaculture Authority Act 2005 (c.4). ACT NO. 24 OF 2005. Delhi: Government of India. [Online]. Available at: https://legislative.gov.in/sites/default/files/A2005-24.pdf (Accessed on 2 March 202)

The Hindu Business Line (2019). *Mud crab hatchery planned in Maharashtra* (March 04). [Online] Available at: https://www.thehindubusinessline.com/economy/agri-business/mud-crab-hatchery-planned-in-maharashtra/article26431772.ece# (Accessed on 13 February 2020).

Thilsted, S. H. (2012). The potential of nutrient-rich small fish species in aquaculture to improve human nutrition and health. Farming the Waters for People and Food. *Proceedings of the Global Conference on Aquaculture* 2010, 57–73.

Thimdee, W., Deein, G., Sangrungruang, C., & Matsunaga, K. (2001). Stable Carbon and Nitrogen Isotopes of Mangrove Crabs and Their Food Sources in a Mangrove-fringed Estuary in Thailand. *Benthos Research*, 56(2), 73–80.

Thompson L. R., Sanders J. G., McDonald D., Amir A., Ladau J., Locey K. J., *et al.* (2017). A communal catalogue reveals Earth's multiscale microbial diversity. Nature, 551, pp. 457–463.

Toufique, K. A., & Belton, B. (2014). Is Aquaculture Pro-Poor? Empirical Evidence of Impacts on Fish Consumption in Bangladesh. *World Development*, 64, 609–620.

Trainer, V. L., Kudela, R. M., Hunter, M. V., Adams, N. G., & McCabe, R. M. (2020). Climate Extreme Seeds a New Domoic Acid Hotspot on the US West Coast. *Frontiers in Climate*, 2, 1–11.

Triño, A. T., & Rodriguez, E. M. (2002). Pen culture of mud crab *Scylla serrata* in tidal flats reforested with mangrove trees. *Aquaculture*, 211(1–4), 125–134.

Trivedi, J. N., & Vachhrajani, K. D. (2013). Taxonomic account of genus *Scylla* (de Haan, 1833) from Gujarat State, India with two new records of species. *Arthropods*, 2(4), 159–171.

Turner, L. M., Alsterberg, C., Turner, A. D., Girisha, S. K., Rai, A., Havenhand, J. N., Venugopal, M. N., Karunasagar, I., & Godhe, A. (2016). Pathogenic marine microbes influence the effects of climate change on a commercially important tropical bivalve. *Scientific Reports*, 6(1), 32413.

Tzeng, T. Der, Pao, Y. Y., Chen, P. C., Weng, F. C. H., Jean, W. D., & Wang, D. (2015). Effects of host phylogeny and habitats on gut microbiomes of oriental river prawn (*Macrobrachium nipponense*). *PLoS ONE*, 10(7), 1–16.

Underwood, A. J. (1997). *Experiments in ecology: their logical design and interpretation using analysis of variance*. Cambridge university press.

United Nations (2015). UN Population Prospects 2015. [Online] Available at: http://esa.un.org/unpd/wpp/ (Accessed February 22, 2021).

Valbi, E., Ricci, F., Capellacci, S., Casabianca, S., Scardi, M., & Penna, A. (2019). A model predicting the PSP toxic dinoflagellate *Alexandrium minutum* occurrence in the coastal waters of the NW Adriatic Sea. *Scientific Reports*, 9(1), 1–9.

Vasko, T. (1988). The Interdisciplinary and Systems Approach: Complement or contradiction? *European Journal of Engineering Education*, 13(3), 257–261.

Vezzulli, L., Brettar, I., Pezzati, E., Reid, P. C., Colwell, R. R., Höfle, M. G., & Pruzzo, C. (2012). Long-term effects of ocean warming on the prokaryotic community: Evidence from the vibrios. *ISME Journal*, 6(1), 21–30.

Vezzulli, L., Moreno, M., Marin, V., Pezzati, E., Bartoli, M., & Fabiano, M. (2008). Organic waste impact of capture-based Atlantic bluefin tuna aquaculture at an exposed site in the Mediterranean Sea. *Estuarine, Coastal and Shelf Science*, 78(2), 369-384.

Vezzulli, L., Pezzati, E., Brettar, I., Höfle, M., & Pruzzo, C. (2015). Effects of Global Warming on *Vibrio* Ecology. *Microbiology Spectrum*, 3(3).

Vipinkumar, V. P., Salim, S. S., Pushkaran, K. N., Harshan, N. K., Salini, K. P., & Sunil, P. V. (2014). The role of Self Help Groups on coastal indebtedness in marine fisheries sector - a case study from Kerala, south India. *Indian Journal of Fisheries*, 61(1), 36–41.

Von Bertalanffy, L. (1972). The History and Status of General Systems Theory. In Klir, G.J. (Ed.), *Trends in General Systems Theory* .John Wiley & Sons Inc.

Waiho, K., Fazhan, H., Quinitio, E. T., Baylon, J. C., Fujaya, Y., Azmie, G., Wu, Q., Shi, X., Ikhwanuddin, M., & Ma, H. (2018). Larval rearing of mud crab (*Scylla*): What lies ahead. *Aq*uaculture, 493(April), 37–50.

Waller, J. D., Wahle, R. A., McVeigh, H., & Fields, D. M. (2017). Linking rising $pCO_2$ and temperature to the larval development and physiology of the American lobster (*Homarus americanus*). ICES *Journal of Marine Science*, 74(4), 1210–1219.

Walton, M.E., Le Vay, L., Lebata., J.H., Binas, J. & Primavera, J.H. (2006). Seasonal abundance, distribution and recruitment of mud crabs (*Scylla* spp.) in replanted mangroves. *Estuarine, Coastal and Shelf Science*, 66, 493-500.

Warth, A. D. (1978). Relationship between the heat resistance of spores and the optimum and maximum growth temperatures of Bacillus species. *Journal of Bacteriology*, 134(3), 699–705.

Webley J.A.C. & Connolly R.M. (2007). Vertical movement of mud crab megalopae (*Scylla serrata*) in response to light: doing it differently down under. *Journal of Experimental Marine Biology and Ecology*, 341, 196–203.

Weeks, S.C., Marcus, V. & Crosser, B.R. (1999). Inbreeding depression in a self-compatible, androdioecious crustacean, Eulimnadia texana. *Evolution*, 53(2), 472-483.

Wei, H., Wang, H., Tang, L., Mu, C., Ye, C., Chen, L., & Wang, C. (2019). High-throughput sequencing reveals the core gut microbiota of the mud crab (*Scylla paramamosain*) in different coastal regions of southern China. *BMC Genomics*, 20(1), 1–12.

Wells, M. L., Trainer, V. L., Smayda, T. J., Karlson, B. S. O., Trick, C. G., Kudela, R. M., Ishikawa, A., Bernard, S., Wulff, A., Anderson, D. M., & Cochlan, W. P. (2015). Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae*, 49, 68–93.

Weng, S.P., Guo, Z.X., Sun, J.J., Chan, S.M. & He, J.G. (2007). A reovirus disease in cultured mud crab, *Scylla serrata* in southern China. *Journal of Fish Diseases*, 30, 133-139.

Whiteley, N. M. (2011). Physiological and ecological responses of crustaceans to ocean acidification. *Marine Ecology Progress Series*, 430, 257–271.

Whyte, K. P. (2013). On the role of traditional ecological knowledge as a collaborative concept: A philosophical study. *Ecological processes*, 2(1), 1-12.

Wijkstrom, U.N. & New, M.B. (1989). Fish for feed: a help or a hindrance to aquaculture in 2000", *Infofish International*, 6 (89), 48-52.

Woolcock, M. (1998). Social capital and economic development: Toward a theoretical synthesis and policy framework. *Theory and Soci*ety, 27, 151-208.

Woolcock, M., & Narayan, D. (2000). Social Capital: Implications for Development Theory, and Policy. *World Bank Research Observer*, 15 (2), 225–249.

World Bank (2012). *Inclusive Green Growth: The Pathway to Sustainable Development*. Washington, DC, The World Bank.

World Bank, Food Agriculture Organization, and WorldFish (2012). *Hidden Harvests: the Global Contribution of Capture Fisheries, Economic and Sector Work Report No. 66469-GLB*. Washington, DC, The World Bank.

Wu, H. C., Dissard, D., Douville, E., Blamart, D., Bordier, L., Tribollet, A., Le Cornec, F., Pons-Branchu, E., Dapoigny, A., & Lazareth, C. E. (2018). Surface ocean pH variations since 1689 CE and recent ocean acidification in the tropical South Pacific. *Nature Communications*, 9(1).

Wurts, W. A. & Masser, M. P. (2013). Liming Ponds for Aquaculture. *SRAC Publication*, 4100.

Xia, J. H., Lin, G., Fu, G. H., Wan, Z. Y., Lee, M., Wang, L., Liu, X. J., & Yue, G. H. (2014). The intestinal microbiome of fish under starvation. *BMC Genomics*, 15(1), 1–11.

Xiong, J. B., Nie, L., & Chen, J. (2019). Current understanding on the roles of gut microbiota in fish disease and immunity. *Zoological Research*, 40(2), 70–76.

Xu, K., Ye, W., Cao, H., Deng, X., Yang, Q., & Zhang, Y. (2004). The role of diversity and functional traits of species in community invasibility. *Bot. Bull. Acad. Sin.*, 45, 149–157.

Xu, X., Wang, G., Zeng, C., & Li, S. (2018). Parentage determination of the mud crab *Scylla paramamosain* using microsatellite markers. *Aquaculture Research*, 49(1), 217–221.

Ye, L., Amberg, J., Chapman, D., Gaikowski, M., & Liu, W. T. (2014). Fish gut microbiota analysis differentiates physiology and behavior of invasive Asian carp and indigenous American fish. *ISME Journa*l, 8(3), 541–551.

Zeng, M., Zhong, Y., Cai, S., & Diao, Y. (2018). Deciphering the bacterial composition in the rhizosphere of *Baphicacanthus cusia* (NeeS) Bremek. *Scientific Reports*, 8(1), 1–11.

Zhang, C., Li, F., & Xiang, J. (2015). Effect of temperature on the standard metabolic rates of juvenile and adult *Exopalaemon carinicauda*. *Chinese Journal of Oceanology and Limnology*, 33(2), 381-388.

Zhang, M., Sun, Y., Chen, K., Yu, N., Zhou, Z., Chen, L., Du, Z., & Li, E. (2014a). Characterization of the intestinal microbiota in Pacific white shrimp, *Litopenaeus vannamei*, fed diets with different lipid sources. *Aquaculture*, 434, 449–455.

Zhang, M., Sun, Y., Chen, L., Cai, C., Qiao, F., Du, Z., & Li, E. (2016). Symbiotic bacteria in gills and guts of Chinese mitten crab (*Eriocheir sinensis*) differ from the free-living bacteria in water. *PLoS ONE*, 11(1).

Zhang, N., Song, C., Wang, M., Liu, Y., Hui, M., & Cui, Z. (2017). Diversity and characterization of bacteria associated with the deep-sea hydrothermal vent crab *Austinograea* sp. comparing with those of two shallow-water crabs by 16S ribosomal DNA analysis*. PLoS ONE*, 12(11), 1–17.

Zhang, X. J., Bai, X. S., Yan, B. L., Bi, K. R., & Qin, L. (2014b). *Vibrio harveyi* as a causative agent of mass mortalities of megalopa in the seed production of swimming crab *Portunus trituberculatus*. *Aquaculture international*, 22(2), 661-672.

Zhou, S., Smith, A. D. M., Punt, A. E., Richardson, A. J., Gibbs, M., Fulton, E. A., Pascoe, S., Bulman, C., Bayliss, P., & Sainsbury, K. (2010). Ecosystem-based fisheries management requires a change to the selective fishing philosophy. *Proceedings of the National Academy of Sciences of the United States of America*, 107(21), 9485–9489.

Zou, S., Xu, W., Zhang, R., Tang, J., Chen, Y., & Zhang, G. (2011). Occurrence and distribution of antibiotics in coastal water of the Bohai Bay, China: impacts of river discharge and aquaculture activities. *Environmental Pollution*, 159(10), 2913-2920.

# Appendix 1: Questionnaires

Fisher survey

Hello. My name is Elina Apine. I am a PhD scholar from Plymouth University in the UK. The research project looks at mud crab collection on the West coast of India.

Thank you for agreeing to participate in this survey. I will take your name but will not publish your name and individual responses. The information provided by you will be used for academic purposes only. You can withdraw from the survey at any time.

If you have any questions about the survey or my research, please contact me, Elina Apine, by email elina.apine@plymouth.ac.uk or by phone 9481074358

Today's date:

Name:

Village/ Gazani:

Location of fishing:

Female /Male

**FISHING ACTIVITIES**

1. **For how long have you been involved in fishing/fishing related activities?**
    1. Up to 1 year
    2. 1 - 3 years
    3. 3 - 5 years
    4. 5 - 10 years
    5. 10 - 20 years
    6. Since childhood
    7. Other (please specify)_____
2. **Have you had any other occupation?** Yes / No

3. **In which sector were you employed?**

1. Agriculture 2. Aquaculture farm (e.g. shrimp farm)
3. Manufacturing 4. Other (please specify)__

4. **Please provide a description of the occupation of your parents, brothers and sisters in the family?**

1. My entire family including parents and other relatives have been involved in fishing and fishery related activities (fish trade, processing, transportation etc)
2. During the last 10 -15 years many members of the family have migrated to other occupations/business/services. Specify their current occupation

   a. ____
   b. ____
   c. ____

5. **Have you been fishing in somewhere else besides your current area?** Yes / No

6. **If yes, where, for how long and what was the reason for migration?**

| Location | Duration (years) | Reasons for migration |
|---|---|---|
| | | |
| | | |
| | | |

7. **Are you involved in fishing currently somewhere else besides this particular area?** Yes/No

8. **If yes please specify location**______________

9. **What type of nets/gear do you own and/or use and for what?**

| Net / gear | Target (fish, crabs, shrimps, bivalves etc.) | Capital costs (if applicable) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

10. **Do you own/use a boat?** Yes / No

11. **If yes, please give these details**

| Type (motorised/non-motorised) | Quantity | How often used | Maintenance/hire costs(fuel/repair) |
|---|---|---|---|
| | | | |

12. **Have you leased a *gazani*/waterbody for fishing?** Yes/No

13. **If yes, please give the following:**

| Total area of*gazani* (ha/acres) | Area of the *gazani* leased (ha/acres) | Number of partners | Duration | Amount received from the contractor (Rs/year) | Total catch inkg | Share of (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Crabs | Prawns | Fish |
| | | | | | | | | |

14. **Who constructed the embankments and sluice gates and who maintains them?**

1. Local Panchayats (local self-govt.)
2. State dept. (public works/Minor Irrigation/Others)
3. Contractor
4. Others (Specify)
5. I don't know

15. **How do you rate the maintenance of these embankments by the authority who built them?**

Very good / good / better /bad / worse

16. **Do you and your neighbourhood invest your labour and capital for the maintenance of these structures?** Yes / No

17. **If yes how much annually?** Capital Rs_Number of labour days_____

*Questions to be asked if mud crab has not been mentioned.*

18. **Do you ever catch green mud crab?**

Occasionally / rarely / never

19. **If never, please explain why.**

___________________________________________________________________________

20. **Would you consider collecting mud crabs?**

___________________________________________________________________________

## MUD CRAB COLLECTION/FISHING

21. **How much mud crabs do you catch depending on the season?**

| Amount in kg/week | Pre-monsoon<br>February - May | Monsoon<br>June - September | Post-monsoon<br>October - January |
|---|---|---|---|
| Green mud crab | | | |
| Red crab | | | |

22. **To whom do you sell collected mud crabs?**

1. To consumers in my local village market  2. To consumers in a market outside my district

3. To middlemen who resell  4. Other/only for personal consumption (please specify)____________________

23. **Could you tell us the price of mud crabs during 2017-18?**

| | <500 grams | 500-1000 grams | >1000 grams |
|---|---|---|---|
| Green mud crab with all limbs without any damage | | | |
| Green mud crab with damage such as lost limb | | | |
| Red crab | | | |

24. **Have you ever caught sick crabs?** Yes / No

25. **If yes, how often?**_____________

26. **How do you identify that the crab is sick?**

_______________________________________________________________________

27. **Do you ever put mud crabs back/is there a minimum size that you catch?**

_______________________________________________________________________

28. **What do you do if you find a female crab with eggs?**

_______________________________________________________________________

29. **Do you consider mud crab collection profitable and stable (constant catch over the years)source of livelihood?**

1. Profitable but unstable
2. Profitable and stable
3. Not profitable and unstable
4. Other (please specify)__________

30. **In your perception what has happened to the mud crab quantity in your area since you havebeen fishing here?**

Significantly increased / slightly increased / stayed the same / decreased / significantly decreased

31. **Please explain your answer in terms of reasons of change or pattern you see.**

______________________________________________________________

32. **Do you retain collected crabs for your family consumption?** Yes / No
33. **If yes, what would be your average weekly consumption (number of crabs/grams)**

_______________________

34. **If never or few times a year, please explain your answer.**

________________________________________________________________

## MUD CRAB CULTIVATION

35. **Are you aware of mud crab fattening and grow-out systems on wild harvesting?** Yes / No
36. **If yes, would you consider undertaking such an enterprise yourself?** Yes / No
37. **If yes, what would encourage you to shift to the crab fattening?**
    1. Subsidies and interest free credit
    2. Education/skills/technology
    3. Location and infrastructure (seeds, feeds, electricity)
    4. Other (please specify)____________________
38. **If no, what are the reasons?**
    1. Not feasible because of low profits
    2. There is no good market demand
    3. This environment/climate (temperature/water-quality) of the region is not suitable for crabfarming
    4. Other (please specify)_______________________

## SCHOCKS AND TRENDS

**39. Would you consider that the area where you are currently fishing is better or worse now since you started fishing here in terms of availability of natural resources (including fish stock, mud crabs, bivalves etc.)?**

| | Better | Worse |
|---|---|---|
| Quantity of fish/crustaceans/bivalves | | |
| Environmental parameters (water flow / pollution) | | |
| Market demand and price | | |
| Other (please specify) | | |

**40. How would you describe the impact of the following environmental on your regular fishing activity including crab harvesting? (Please tick)**

| | No impact | Minimal | Moderate | Significant | Positive | Negative |
|---|---|---|---|---|---|---|
| Flood | | | | | | |
| Increase of freshwater | | | | | | |
| Saltwater intrusion | | | | | | |
| Erosion/sea level rise | | | | | | |
| Water pollution and temperature | | | | | | |
| Expansion of mangrove area | | | | | | |
| Other (please specify) ___________________ | | | | | | |

**41. How would you describe the impact of these factors to you as a fisher? (please tick)**

| | No impact | Minimal | Moderate | Significant | Positive | Negative |
|---|---|---|---|---|---|---|
| Industries/companies (including aquaculture farms and industrial fishing) along the coast | | | | | | |
| State infrastructure development projects (roads/harbors) | | | | | | |
| Fishing intensity (increased number of fishers within the river/ estuary) | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sand mining | | | | | | |
| Tourism | | | | | | |
| Other (please specify ______________________________ | | | | | | |

## STRUCTURES AND PROCESSES (INSTITUTIONS AND TRUST)

42. **Are there any organisations supporting you with training or information or in any other way? Please indicate which and explain how.**

______________________________________________________________________

43. **If your household would be affected by natural disaster/financial problems/social problems etc., who would you turn for help to?**

| Fact or | Not at all likely | Probably | Most likely |
|---|---|---|---|
| Family outside the household (relatives/friends) | | | |
| Community group | | | |
| NGOs | | | |
| Panchyats | | | |
| District Administration (Tahsiladar)/Fisheries Dept. | | | |
| Informal or traditional leader | | | |
| Other (please specify) _________________________ | | | |

## INDIVIDUAL AND HOUSEHOLD INFORMATION

| Age (respondent) | Mother tongue | Religion | Education (in years) |
|---|---|---|---|
| | Kannada / Konkani / Urdu / Other (please specify): | 1. Hindu (SC/ST/OBC/Others)<br>2. Muslim<br>3. Christian<br>4. Other (please specify): | |

**Are you the head of the household?** Yes / No

**If no, how are you related to the head of the household**? _____
**Household size:**

Number of adults_____Male___Female

Number of children_____Male_______Female_

**Share from mud crab harvesting constituting to the total monthly household income**

1. Only for self-consumption 2. Up to 25% 3. 25-50% 4. 50-75% 5. Above 75%

Crab farmer survey

Hello. My name is Elina Apine. I am a PhD researcher from the University of Plymouth in the UK. In this research project I am investigating small-scale mud crab farming in south India.

Thank you for agreeing to participate in this survey. Your responses will remain anonymous and no individual responses will be published. The information provided by you will be used for academic purposes only. Your participation in this study is completely voluntary and you can skip questions or withdraw from the survey at any time.

If you have any questions about the survey or my research, please contact me, Elina Apine, by email elina.apine@plymouth.ac.uk or by phone (+91) 7019421658

## MODULE A. RESPONDENT IDENTIFICATION

| QUESTION | ANSWER |
|---|---|
| **A1.01:** Date of visit | ________dd/_________mm/ 2019 |
| **A1.02**: Location name | |
| **A1.03**: GPS coordinates | |
| **A1.04:** Code of respondent | |

## MODULE B. MUD CRAB FARMING

## B1 FARMING

| QUESTION | ANSWER (circle or write) | | | |
|---|---|---|---|---|
| **B1.01**: What do you farm? | 1= only mudcrabs | 2= mud crabs andother species of crabs (please specify what) | 3= mud crabs andfish (please specify what) | 4= mud crabs, other species of crabsand fish (please specify what) |
| **B1.02**: For how long have you been undertaking aquaculture? | | | | |

| | | | |
|---|---|---|---|
| **B1.03:** For how long youhave been farming mud crabs? | | | |
| **B1.04**: What type of mudcrab farming do you have? | 1= fattening | 2= grow-out fromwild seeds (juveniles) | 3= grow-out from commerciallyavailable seeds from hatcheries |
| **B1.05**: Where do you keep your mud crabs in? | 1= earthen pond | 2= mangrove incorporated pen | 3= other (please specify) |
| **B1.06**: How big in acres isyour pond (s)/pen(s)? How many ponds do you have? | | | |
| **B1.07:** Where do you obtain mud crabs/seeds from? | | | |
| **B1.08**: How many crabs/ seeds did you buy for the | | | |
| last stocking of the pond? Specify the date. | | | |
| **B1.09**: How many mud crabs did you have at the last harvest? How much in weight (kg)? | | | |
| **B1.10:** For how long do you keep them in the pond (How long takes the full culture?) | | | |
| **B1.11:** Do you practice partial harvesting? If yes, how many types per crop? | | | |
| **B1.12:** What type of feed do you use and how much per day? | | | |
| **B1.13:** How do you increase the feed quantityas the animal size increases? | | | |
| **B1.14:** Do you harvest the feed yourself? | | | |

| | | |
|---|---|---|
| **B1.15:** Do you give any additional probiotics? | | |
| **B1.16:** How do you prevent crabs fromescaping? | | |
| **B1.17:** Do you plan tocontinue mud crab farming? | 1= YES | 2= NO, explain |
| **B1.18:** If you have alreadystopped farming crabs, what was the reason? | | |

## B2 Access to land and water

| QUESTION | ANSWER (circle or write) | | | |
|---|---|---|---|---|
| **B2.01**: Do you own or lease in the land your pond(s) islocated? | 1= Own (go to B2.02) ………………… acres | 2= Lease (go to B2.04). …………………. acres | | |
| **B2.02:** Did you inherit or bought the land? | 1= Inherited | 2= Bought | | |
| **B2.03:** Do you have any additional land that could be used for aquaculture? | 1= YES .......... acres | 2= NO | | |
| **B2.04:** Who do you lease theland from? | 1= local or state government | 2= relatives | 3= other privat e owners | 4= common land |
| **B2.05:** Do you get any loan to partly or fully cover the lease expenses? If yes, what is the proportion of lease covered by the loan? | 1= YES, from statebanks The proportion - | 2= YES, from private banksor private organisations The proportion- | 3= YES, from middlemen or crab processors | 4= NO |
| **B2.06**: What is the sourceof the water if the crabs are cultivated in the pond? | | | | |
| **B2.07**: How do youmaintain the water quality? | | | | |

| | |
|---|---|
| **B2.08**: Have you any issueswith water pollution?<br>Explain | |

## B3 PERCEPTION OF MUD CRAB FARMING

**B3.01: What difficulties do you have to face while being involved in mud crab farming?**

| |
|---|
| |

**What are the limitations?**

**Please assess how difficult or easy, in your perception, is to access the following? (tick the appropriate box)**

| | | 1=Easy | 2= Somewhat difficult | 3= Very difficult |
|---|---|---|---|---|
| **B3.02** | Seedlings/small crabs | | | |
| **B3.03** | Feed for mud crab | | | |
| **B3.04** | Land | | | |
| **B3.05** | Fish markets or middlemen | | | |
| **B3.06** | Training or farming methods | | | |
| **B3.07** | Subsidies | | | |
| **B3.08** | Loans | | | |
| **B3.09** | Water supplies | | | |

**Please indicate whether you agree or disagree with following statements (Tick the appropriate):**

| | Statement | Agree | Disagree |
|---|---|---|---|
| **B3.10** | Mud crab farming is a profitable activity | | |
| **B3.11** | Mud crab farming is a stable source of income | | |
| **B3.12** | I receive enough support from various organisations (financial, training) | | |
| **B3.13** | I would expand farming if I received support | | |
| **B3.14** | I would encourage my friends and family to<br>undertake mud crab farming | | |

## MODULE C. ACCESS TO MARKET AND EXTENSION AND ADVISORY SERVICES

### C1 MARKET AND SALES

| QUESTION | ANSWER (circle or write) | | | | |
|---|---|---|---|---|---|
| **C1.01:** Where do you sell your mud crabs to? | 1= to a middleman | 2= to the local market directly | 3= both | 4= other (please specify) | |
| **C1.02**: What is the selling price of the mudcrab at the moment? | | | | | |
| **C1.03**: Is the selling price fluctuating? | 1= YES | 2= NO | | | |
| **C1.04:** Do you know where middleman are further reselling crabs? | 1= YES, for export | 2= YES, within Andhra Pradesh | 3= YES, other (pleasespecify) | 4= NO | |
| **C1.05:** How satisfied areyou with service and prices middleman offers you? | 1= very satisfied | 2= somewhat satisfied | 3= neutral | 4= not very satisfied | 5= completely unsatisfied |
| **C1.06:** Does the middleman offer loans? | 1= YES and Ihave used it | 2= YES, but I have not used it | 3= NO | 4= I don't know | |
| **C1.07:** Do you have acontract with the middleman and if yes what are the conditions? | 1= YES, explain the conditions | 2= NO | | | |
| **C1.08:** How do you transport your crabs to the middleman or to the market? | 1= Using public transport | 2= Using my owntransport | 3= Organised transport by the middleman/processing company | 4= Other (please specify) | |
| **C1.09:** Do you consumemud crabs yourself? If yes how much per week/month? If not, why? | 1 = YES | 2 = NO | | | |

## C2 SOURCES OF INFORMATION AND SUPPORT FROM ADVISORY SERVICES

**Where do you receive information about mud crab and fish farming from? (Tick the appropriate)**

| | **Source of information** |
|---|---|
| **C2.01** | Mass media |
| **C2.02** | Traders association/State fisheries department |
| **C2.03** | Feed company/midllemen |
| **C2.04** | Other………………………………………………………. |

**Which advisory or extension offices have offered training to you? (Tick the appropriate)**

| | **Advisory or extension offices** | |
|---|---|---|
| **C2.05** | State fisheries department | |
| **C2.06** | MPEDA | |
| **C2.07** | University or college staff or students | |
| **C2.08** | CMFRI | |
| **C2.09** | Feed company or middlemen (crab dealers/processors) | |
| **C2.10** | Other (please specify) | |

## MODULE D. PRODUCTION COSTS

**D1.01: Please indicate the costs of these fixed capitals and whether you received a support in the form of loan or subsidy?**

| **Fixed capital** | **Costs (per month or year,specify)** | **Is it covered by a loan or subsidies? (explain and indicate howmuch). If rented the equipment, how much did it cost?)** |
|---|---|---|
| Land (lease) | | |
| Setting up the pond (digging/liming/fences) | | |
| Setting up the pen (fences) | | |
| Interest rate for existing loans | | |
| Other | | |

**D1.02: Please indicate the costs of these variable capitals and whether you received a support in the form of loanor subsidy?**

| Variable capital | Costs (per month or year, specify) | Is it covered by a loan or subsidies? (explain and indicate howmuch). |
|---|---|---|
| Crab seedlings or small adult crabs | | |
| Feed | | |
| Maintenance | | |
| Transportation costs | | |
| Labour | | |
| Water/electricity costs | | |
| Other | | |

**D1.03:** How many employees do you have? How many of them are female and what is their task?

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## MODULE E. MUD CRABS AND THE ENVIRONMENT

| QUESTION | ANSWER | | | | |
|---|---|---|---|---|---|
| **E1.01:** If you rely on wild caught crabs, in your perception what has happenedto the wild mud crab quantity in your area? | 1= significantl y increased | 2= slightly increase d | 3= stayed thesame | 4= slightly decrea sed | 5= significantl y decreased |
| **E1.02:** Please explain your answer in terms of reasons ofchange or patterns you see. | | | | | |
| **E1.03:** Have you noticed sickcrabs? If yes, what were the signs? | 1= YES | 2= NO | | | |

**How would you describe the impact of the following environmental on mud crab farming and fishing (if you are involved)?(Please tick)**

| | No impact | Minimal | Moderate | Significant | Positive | Negative |
|---|---|---|---|---|---|---|
| **E1.04** Flood | | | | | | |
| **E1.05:** Increase of freshwater | | | | | | |
| **E1.06:** Saltwater intrusion | | | | | | |
| **E1.07:** Erosion/sea level rise | | | | | | |
| **E1.08:** Water pollution and temperature | | | | | | |
| **E1.09:** Mangrove destruction | | | | | | |
| **E1.10:** Other (please specify) | | | | | | |

**E1.11: How do you manage increasing water temperature? Does it influence mud crab growth and how?**

______________________________________________________________

## MODULE F. DEMOGRAPHICS

| QUESTION | ANSWER | |
|---|---|---|
| **F1.01**: Gender | 1=M | 2=F |
| **F1.02:** Number of years of schooling | | |
| **F1.03:** What is your age? | | |
| **F1.04:** Mother tongue | | |
| **F1.05:** Religion | | |

**F1.06: Please indicate up to three sources of your household income and provide the proportion of income inpercent.**

| | Source of income | Proportion (%) |
|---|---|---|
| Primary source of income | | |
| Secondary source of income | | |
| Tertiary source of income | | |

**If the proportion of income on mud crab farming is not provided above:**

| | | | | | |
|---|---|---|---|---|---|
| **E1.07** Share from mud crab farming constituting to the total monthly household income | below 10% | 10-24% | 25-49% | 50-74% | 75% and above |

Thank you very much for taking the time to participate in this survey!

# Appendix 2: Detailed information on crab farms

| ID | Scale (small <2ha; large >2.01 ha) | Total area (ha) | Duration in months | Total number of instars stocked | Total number of crablets stocked | Total numbers of crabs sold | Total amount in kilograms sold |
|---|---|---|---|---|---|---|---|
| N1 | small | 0.608 | n/a | - | 1800 | 250 | 125 |
| N2 | large | 2.025 | n/a | - | 6000 | 1000 | 500 |
| N3 | small | 0.81 | n/a | - | 2400 | 0 | 0 |
| N4 | small | 0.405 | n/a | - | 1200 | 50 | 45 |
| N5 | small | 1.215 | n/a | - | 1800 | 100 | 100 |
| N6 | small | 0.405 | n/a | - | 500 | 100 | 50 |
| N7 | small | 1.013 | n/a | - | 200 | yet to harvest | |
| T1 | small | 0.81 | 4 | - | 1300 | 300 | 180 |
| G1 | small | 0.405 | 5 | - | 500 | 0 | 0 |
| NA1 | large | 16.2 | 3 | 18000 | 4000 | 900 | 450 |
| NA2 | large | 2.025 | 6 | - | 2000 | 250 | 125 |
| NA3 | large | 2.025 | 5 | - | 1000 | 500 | 250 |
| NA4 | large | 5.265 | 5 | - | 6400 | 300 | 150 |
| NA5 | large | 2.43 | 5 | - | 3000 | 250 | 125 |
| S1 | large | 12.15 | 4 | 10000 | - | 50 | 25 |
| S2 | large | 2.025 | 4 | 2000 | - | yet to harvest | |
| S3 | large | 4.05 | 4 | 3000 | 1200 | yet to harvest | |
| S4 | large | 3.24 | 7 | 3200 | - | yet to harvest | |
| S5 | small | 1.62 | 4 | 2000 | 800 | 400 | 200 |
| S6 | large | 3.645 | 4 | 4500 | 2700 | 0 | 0 |
| TA1 | small | 2 | 6 | 3000 | - | - | 400 |
| TA2 | small | 1 | 6 | 3000 | - | - | 400 |
| TA3 | small | 1 | 6 | 3000 | - | - | 400 |
| TA4 | small | 2 | 6 | 4000 | - | n/a | n/a |
| PE1 | small | 1 | 6 | 2000 | - | - | 380 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PE2 | small | 1 | 6 | 2000 | - | - | 380 |
| PE3 | small | 1 | 6 | 2000 | - | - | 380 |
| CHI1 | small | 1.62 | 8 | 3000 | - | 1800 | 900 |
| CHI2 | large | 4.05 | 8 | 5000 | - | 1500 | 750 |
| CHI3 | small | 1 | 8 | 5000 | - | 1500 | 750 |
| CHI4 | large | 4.05 | n/a | 4000 | - | 0 | 0 |
| CHI5 | small | 2 | 5 | - | 2300 | 50 | 25 |
| CHI6 | small | 0.81 | 5 | 200 | - | 100 | 10 |
| CHI7 | small | 1.62 | n/a | - | - | 0 | 0 |
| KA1 | small scale | 1.82 | 7 | 2000 | - | yet to harvest | |
| KA2 | small | 1.22 | 4 | 2000 | - | 800 | 250 |
| KA3 | small | 1.22 | 4 | 1000 | - | yet to harvest | |