Evaluating ecosystem interventions for improved health outcomes – The case of the Volta Estuary mangroves and malaria

Emma Marjorie Awuku-Sowah

BSc., MSc.

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Lancaster Environment Centre

Faculty of Science and Technology

Lancaster University

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ABSTRACT

Evaluating Ecosystem Interventions for Improved Health Outcomes: The Case of the Volta Estuary Mangroves and Malaria – Emma M. Awuku-Sowah

Degradative alteration of ecological systems worldwide is progressing at a time when their influence on human wellbeing is becoming more evident. For some ecosystems and aspects of wellbeing, more concrete knowledge exists. Insights into the science of mangrove-health relationships are however limited and fragmented, with no assessments of human perspectives around these phenomena.

This study investigated the nature of the mangrove-human health nexus by assessing the impacts of mangrove ecosystem interventions on health-related ecosystem goods and services and self-reported malaria experiences. Using a mix of methods comprising a systematic literature review, key informant interviews, health questionnaires and Qualitative Comparative Analysis (QCA), this study merges three bodies of work. Research participant viewpoints were synthesized regarding the evolution of mangrove characteristics and use patterns over time, and how these are affected by ecosystem restoration. Survey respondents were also engaged in a recall exercise of malaria experiences over the same period, to provide a basis for causal inference analysis using QCA methodology. Results show that mangrove dependence is declining with ecosystem degradation in Ghana, but ecosystem restoration can modulate some negative health impacts of mangrove degradation, such as infectious disease risk and threats to protein nutrition. Further, specific ecological conditions elicited by ecosystem interventions work together diversely to decrease malaria incidence, but mainly to amplify benefits of current malaria vector control interventions.

The causal relationships reveal that certain aspects of wetland restoration can be strengthened to deliver conditions that improve consequences of current malaria management strategies. Environment and health managers must collaborate in policy reorientation, monitoring, evaluation, and capacity building to realise more tangible scientific evidence and sustainable cross-sector outcomes. Ecosystem interventions could plug the shortfalls arising from resource constraints in health policy implementation, towards more uniform outcomes especially in marginal communities.

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List of Abbreviations

AfriMAB	Man and Biosphere Regional Network for Africa
AIDS	Acquired Immune Deficiency Syndrome
BCA	Biological Control Agents
CCAA	Climate Change Adaptation in Africa
CHPS	Community Health Planning and Services
CNY	Chinese Yuan
DAG	Directed Acyclic Graph
DDT	Dichlorodiphenyltrichloroethane
DFID	Department for International Development
EDI	Estimated Daily Intake
FAO	Food and Agriculture Organization
fsQCA	Fuzzy Set Qualitative Comparative Analysis
GEF	Global Environment Facility
GHS	Ghana Health Service
GIS	Geographical information Systems
GMP	Global Malaria Programme
GSS	Ghana Statistical Service
HIV	Human Immuno-Deficiency Virus
IDRC	International Development Research Centre
IHME	Institute for Health and Metrics Evaluation
IRS	Indoor Residual Spraying
ITN	Insecticide Treated Net
ITTO	International Tropical Timber Organization
IUNCN	International Union for the Conservation of Nature
IWQ	Improved Water Quality
MA/MEA	Millennium Ecosystem Assessment
MCES	Marine and Coastal Ecosystem Services
MLC	Mangrove Land Conversion
MOH	Ministry of Health
MPM	Malaria Preventive Measures

NGO	Non-Governmental Organization
NMCP	National Malaria Control Programme
PA	Physician Assistant
PAH	Polycyclic Aromatic Hydrocarbons
PCA	Principal Component Analysis
PCB	Polychlorinated Biphenyls
PERI	Potential Ecological Risk Index
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PTPIB	Tyrosine Phosphatase IB
QCA	Qualitative Comparative Analysis
RAT	Reduced Ambient Temperature
RDT	Rapid Diagnostic Test
REDD	Reducing Emissions from Deforestation and Forest Degradation
RfD	Reference Dose
RMI	Reduction in Malaria Incidence
RQ	Research Question
SCM	Structural Causal Modelling
SMP	Seasonal Malaria Chemoprevention
SWAT	Soil and Water Assessment Tool
THQ	Target Hazard Quotient
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change
UNGA	United Nations General Assembly
UNICEF	United Nations Children’s Fund
USAID	United States Agency for International Development
WHO	World Health Organization

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I acknowledge every effort exerted by my PhD Appraisal Committee members to ensure that I met all my programme milestones on time. Special thanks to Dr Jacob Phelps for suggesting a useful methodological approach that turned out to be a vital component of the research design of this thesis.

Dedication

I wish to dedicate this work to my closest friends and immediate family, who encouraged me before and during this journey, and believed in me even when my own confidence occasionally wavered.

To Dawn and Elaine - my greatest, most challenging project yet; I hope this inspires you someday to pursue your aspirations provided life and strength exist.

Author Declaration

This thesis is the original work of the author, except where otherwise stated, and is not the result of joint research. It has not been submitted for the award of a higher degree at this or any other institution.

Modified version of Chapters 5 and 6 of this thesis have been submitted as manuscripts for peer review and potential publication in two separate journals.

A manuscript based on Chapter 4 has been published in *Wellbeing, Space and Society* open access journal at:
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A journal-formatted version of Chapter 3 has been published as a systematic review paper in the *Dialogues in Health* open access journal, at:
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CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT AND RATIONALE

Most environmental decision-making has often been biased towards more easily quantifiable but not necessarily critical ecosystem services, leaving out those that make life worth living such as are related to health (Diaz *et al*, 2006). For example, mangrove ecosystem services connected to livelihoods and local economies (food production, forest products, etc.) have been extensively studied and documented, with valuation protocols severally applied to justify interventions that preserve them (Field, 1999; Spalding, 2010; De Groot et al., 2002; Barbier et al., 2011). Some comparative paucity however exists in the research coverage of less quantifiable improvements in well-being that could be gained from mangrove ecosystem rehabilitation. Nonetheless, benefits of this nature are crucial, especially where they impinge on the overall health of populations whose livelihood activities hold up local economies, and their values should be given similar weight.

Therefore, for the impact of mangrove restoration to be comprehensively meaningful, it must do more than merely deliver environmental conservation. This is especially significant as the academic space encounters more convincing evidence on links between ecosystem integrity and human wellbeing (Bayles et al., 2016).

As suggested by Macintosh and Ashton (2002) mangroves have consistently been undervalued because only the direct goods and services they provide have been considered, so that urban development has progressively favoured their loss. This situation might not be the case if the full extent of services from such ecosystems were to be considered. Anthropogenic interferences in mangrove ecosystems influence a myriad of structural and ecological alterations within the ecosystem. Notable among these are the impacts on specie distribution, behaviour, and abundance; and, therefore the incidence and prevalence of vector-borne diseases such as malaria. According to Walsh *et al*., (1993) there is evidence of changes in vector ecology and behaviour as well as disease patterns in West and Central Africa; and, especially with malaria, each incidence of deforestation and land transformation has a different impact on specie distribution, directly or indirectly (Stresman, 2010).

Malaria is a hyper-endemic health problem in Ghana, accounting for close to half of aggregated outpatient turnout in public health facilities, and nearly 15% of mortality cases (Asante and Asenso-Okyere, 2003). Despite huge investments into combatting the disease and progress made in that regard, it nonetheless remains a health threat in the country, due to its widespread distribution and resistance to treatment among other factors (Wilcox and Colwell, 2005). Incidence and transmission rates of the disease are however dependent on local conditions and disturbances. Distinctive multi-faceted investigations that integrate variabilities in ecological, economic, and epidemiological characteristics, can confer some contextual reflections for improved control strategies. Particularly, policy directions that downplay the full expanse of ecological considerations that influence vector and parasite life cycles must be re-examined (Pattanayak et al., 2006).

The United Nations Environment Programme and the World Health Organisation along with other project partners, mention the possible links between mangrove loss and heightened malaria incidence as a reason to protect the ecosystem. This is because mangrove loss constitutes a grave disruption in ecosystem integrity, and may have an impact on health and well-being in neighbouring communities (Tyrrell et al., 2008). Many of the poorest regions of the world are the same locales where forest degradation of various forms is widespread; and, at the same time malaria prevalence is high (Pattanayak et al., 2006). In designing policies for combatting malaria, the interactions that it shares with poverty and deforestation become significant. Precisely, appraisals of the extent to which cross-effects occur in terms of how intended and incidental consequences of forest degradation and poverty reduction strategies affect malaria risk are crucial (Wilcox and Colwell, 2005). The thought behind this assertion is the conviction that malaria control agenda could be potentially enhanced by the incorporation of research-supported knowledge that scrutinises this peculiar malaria, livelihoods, and degradative deforestation nexus. In their coupled human-natural system model for the links between deforestation and malaria, Bauhoff and Busch

(2018) describe a conceptualisation for such a nexus, which incorporates variables likely to affect whether a person contracts malaria (Figure 1).

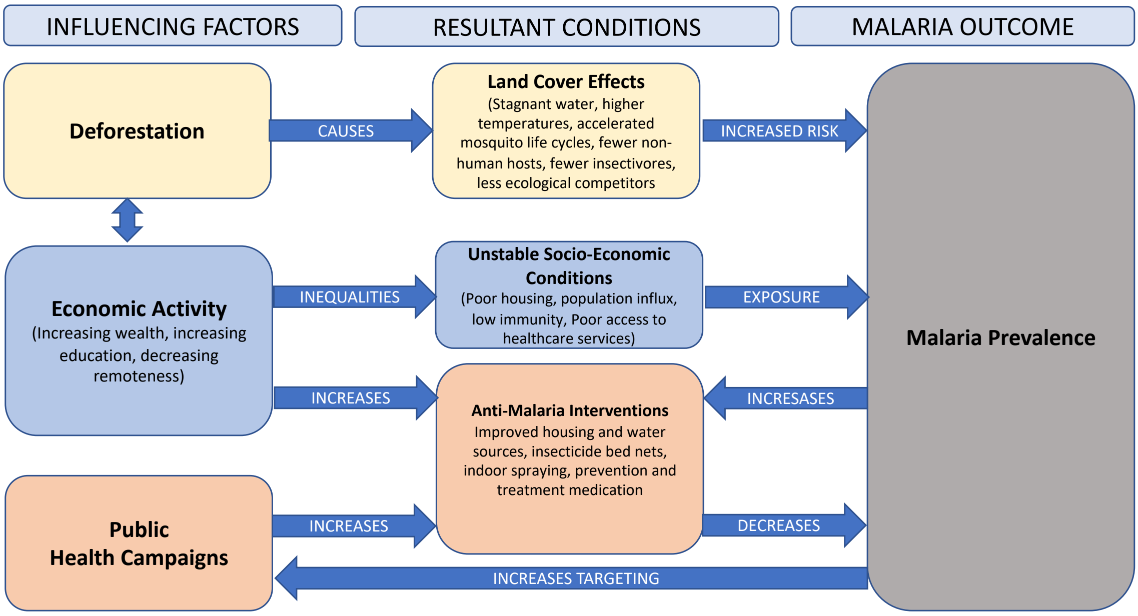

Figure 1: Modified model of deforestation-malaria prevalence nexus as conceived by Bauhoff and Busch (2018), depicting variation of malaria prevalence with conditions dictated by deforestation alongside concomitant impacts of economic development and public health campaigns. Also incorporated are the feedback mechanisms between malaria outcomes and these modifying conditions.

The unstable and risky economic activities that particularly characterize frontier economies such as Ghana, which rely heavily on natural resource exploitation, lead to widespread deforestation. At the same time, inequalities predominant in such economies can precipitate unstable socio-economic conditions that can worsen malaria prevalence. The ecological consequences of deforestation also aggravate malaria risk, although the associated rise in prevalence triggers remedial public health interventions including anti-malaria measures. With rising economic activity and malaria prevalence, more people are incentivized and provided with access to such interventions, thereby decreasing malaria prevalence. A research agenda is required that is directed not only at exposures to ecological conditions suspected to be unhealthy, but also at those that are presumed to be healthy, and at outcomes that reflect states of human health. 'States of health' in this study is defined by a decline in the incidence of febrile disease (and therefore malaria), the main cause of morbidity in Ghana. Challenges however exist in the areas of definition, development, validation, and operationalization of variables that reflect population health, and establish associations between exposure to varied ecological circumstances and health outcomes (Frumkin, 2001). This study is directed at contributing towards addressing this need, and at providing solid impetus for anthropogenic ecosystem interventions (beyond livelihoods enhancement and biodiversity conservation), especially for the benefit of directly dependent populations.

This piece of scholarship investigates how mangrove deforestation-restoration variables work alongside public health interventions to influence malaria experiences within coastal mangrove communities in Ghana. Mangrove is the focus because it is a type of landcover that is neglected as compared to other terrestrial ecosystems when it comes to evaluations of their impacts on community and global health (Barbier, 2012). Apart from mangrove value to cultural, recreational, 'spiritual' and social cohesion aspects of wellbeing, (Friess et al., 2020) not much is reported about physical health dimensions. Meanwhile, preliminary empirical evidence from evaluations undertaken on a rehabilitated[1] mangrove ecosystem suggests that access to 'basic material for a good life' as a component of well- being (see MA, 2005) has been improved by ecosystem interventions (Awuku, 2009). Similarly, evaluations could be conducted to link ecosystem states to health as another well-being aspect, using a methodology that efficiently estimates changes to ecological integrity and human health indicators. In this instance, malaria is used as health proxy because its prevalence depends on established ecological underpinnings, and it further presents a heavy health and socio-economic burden in the tropical regions where mangroves thrive (The global fund, 2016).

In this evaluation, an integrated participatory appraisal of ecosystem conditions within rehabilitated mangroves, considered in tandem with evolving malaria incidence dynamics at the case study sites, is presented. In the first instance a review of the current knowledge from various parts of the world regarding how mangrove ecosystems are linked to different determinants of physical health is conducted. This is followed by a sampling of perspectives from key informants regarding the ways mangroves impact human health specifically within the Ghanaian context, and the difference ecosystem

[1] Rehabilitation as used in this context refers to replanting of mangrove trees within a degraded ecosystem, with the view to catalysing a cascade of ecological and structural events that result in restoration of that ecosystem.

restoration makes. Subsequently, a narrowed-down inquiry is conducted into the nature of malaria incidence over time within satellite communities of mangrove ecosystems bordering the estuary of the Volta River. Perceived states of health are defined in participant responses by the presence of malaria symptoms (including fever, headaches, sweating, and shivering) associated with plasmodic parasitaemia (Diop *et al*, 2006). These perspectives are articulated through responses to assisted health questionnaires, which data is then subjected to a causal inference technique, relying on Qualitative Comparative Analysis (QCA) (Ragin, 2009) methodology. This step is employed to identify causal relationships between reported mangrove ecosystem restoration-elicited conditions, and malaria incidence outcomes. Finally, findings are applied in proposing policy reformative ideas for optimizing contribution of mangroves and similar ecosystems to transformation of malaria control and health management agenda in the case study location and beyond.

1.2 RESEARCH DESIGN

This study adopts a phenomenological, mixed methods approach, with use of an initial qualitative strategy because the research problem is quite complex, with no clearly defined assessment variables within the research arena. One motivation is to contribute to future development of instruments for measuring the most relevant variables identified. This is additionally a concurrent triangulation style case study, utilizing a mix of key primary data collection strategies (observations, key-informant interviews, and assisted health questionnaires), as well as secondary data in an additional validation step. Due to the intention to capture perceptions about certain changes, not just across spatial scales but also over time, a purposeful quota sampling plan is used, to specifically include only age groups that can appreciate the timeframes involved.

Data processing comprised coding, categorisation, and theme development from qualitative data (key informant interviews) followed by use of fsQCA software as a statistical tool to generate Boolean algebra-style causal recipes. QCA methodology is used to investigate causality relationships between the restoration related mangrove ecosystem conditions on one hand; and perceived changes in malaria incidence patterns captured in the quantitative questionnaire data on the other.

The presumptive notion informing this design is that ecosystem integrity, and therefore functioning, stands to be positively impacted by the protective management of the mangrove forest following replanting. The eventual exploration of this idea with respect to malaria, as mentioned earlier, is premised on the role that ecosystem integrity plays in the dynamics of the life cycle of the prevalent plasmodium vectors. Anthropogenic interferences often result in alterations in mangrove ecosystem subtleties, which primarily make newer breeding habitats and conditions available for malaria vectors. Ecosystem boundaries are re-shaped the forest frontier is also moved closer to human settlements, and the increased possibility of contact with vector organisms is postulated to lead to greater incidence of the disease (Gottwalt, 2013). Since vector control is one of the most crucial management strategies in malaria control, the dynamics of this dimension becomes truly relevant in the malaria incidence conversation. De Groot (1992) describes ecosystem functioning as the capacity of ecological processes and structures to provide ecosystem services that satisfy human well-being. The concept of "ecological integrity" provides a useful framework for selecting monitoring variables of ecosystem functioning, and for assessing progress by natural or man-made agents of change toward ecologically based management goals. It measures an ecosystem's composition, structure, and function, compared with its natural or historical range of variation (Tierney et al, 2009), an assessment viewed as suitable for this research. Perceived states of mangrove ecosystem integrity are thus evaluated alongside perceived states of health.

1.2.1 Research Questions

The aim of this research is to improve understanding of the relationship between the state of mangrove ecosystem integrity, as defined by the extent of forest degradation, and malaria incidence within neighbouring populations, as an index of health and wellbeing. In resolving this overarching aim, the following research questions are addressed:

RQ1. What are the current and potential health-related goods and services supplied by mangrove ecosystems as reported in the literature?

RQ2. How have mangrove use and ecosystem states evolved alongside human health experiences within the case study location, and what difference does forest restoration make?

RQ3. What is the nature of the causal relationship between mangrove ecosystem integrity changes, and malaria incidence characteristics within the study sites following interventions?

RQ4. What do mangrove ecosystem-related risk factors mean for current malaria and ecosystem management regime in the region; and what are the policy advancement opportunities?

1.2.2 Research Objectives

To address the outlined research questions, a research methodology is adopted that follows the thesis structure in Figure 2, and with the following specific objectives:

1. To review current knowledge about value of mangrove ecosystems, drivers of mangrove ecosystem degradation, and the potential ecological effects of mangrove ecosystem integrity on malaria transmission factors (CHAPTER 2)
2. To conduct an additional systematic review of academic evidence about the ways in which mangrove ecosystems impact physiological health in regions around the world (Via research sub-questions RQi to RQiv in CHAPTER 3)
3. To sample views of key informants about how the findings of the systematic review in chapter 3 relate to the situation in Ghana; with respect to mangrove-human interactions and impacts on human health over time (Via research sub-questions RQv to RQvii in CHAPTER 4)
4. To employ assisted health questionnaires and QCA methodology in analysing the causal relationships between mangrove ecosystem conditions and reported malaria incidence outcomes, based on proximity to degraded or reforested mangrove ecosystems (Via research sub-questions RQviii to RQxi in CHAPTER 5)
5. To resolve how causal inferences about mangrove links to malaria could be applied to improve ecosystem and health management regimes in Ghana and similar locations and situations elsewhere (CHAPTER 6)

1.2.3 Research Positionality Statement

I wish to present some researcher self-reflexivity information before presenting the findings of my research as they relate especially to Chapters 4 and 5.

While I no longer reside permanently in Ghana, I acknowledge my standpoint as Ghanaian woman who was born and raised in a society that is at perennial risk of malaria infection. I have experienced multiple personal bouts of debilitating malaria infection, which were severe but successfully treated. I concede that these experiences might influence my perception of malaria as a major determinant of human health in Ghana, the way I frame and questions around malaria experiences. However, having also observed others' experiences of the disease, and can more confidently conclude that my personal perceptions of malaria characteristics are shared by many.

Given my graduate-level education, I also recognize my bias for factual rather than anecdotal information, and I might have paid less attention to constructs of nature and disease that do not align with established truths. This may have been accompanied by an inclination to extend conversations around more of such established concepts. I have, however, made the conscious effort to be balanced in interpreting lived experiences of others, and to report all variations in their perspectives and reasoning. This was achieved through consistent notetaking throughout the data collection process, to document all uncommon, unfamiliar, and unexpected observations.

I have never lived in a subsistence community; therefore, I am not familiar with patterns of natural resource exploitation from my surroundings. However, by collaborating with environmental management practitioners from the Wildlife Division of Ghana's forestry commission, I believe that any related misinterpretation of meanings in this area of the research would have been brought to my attention. These partners, unlike me, were aware of resource use dynamics in the study locations. Although I do not speak local languages of these locations, I trust that these collaborators, who had conducted similar research procedures in the past, facilitated the best possible knowledge transfer scenario via their excellent translation services.

1.3 THESIS STRUCTURE

Following the introduction chapter is a preliminary literature review of the study in CHAPTER 2. It identifies drivers of mangrove land use alterations in Ghana, and the ecological foundations of mangrove ecosystem integrity in general. It also tracks the rationale and expectations of restoration, along with a presentation of the malaria outlook and management situation in Ghana. This is followed by a more targeted PRISMA-styled[2] systematic review of literature in CHAPTER 3, with a focus on the health benefits derived from mangrove ecosystem goods and services as reported in the Web of Science database. This constitutes the desk-based aspect of the research.

For a comparative evaluation, the second phase of the research was directed at positioning the Ghanaian situation within the general context formed from the most widely reported mangrove-health links as captured in CHAPTER 3. It comprised key informant interviews in CHAPTER 4 regarding how ecosystem integrity, as projected by the intervention delivered by reforestation efforts, has been changed in parallel to public health management advancement in the case study site. Supplementary health data on malaria was obtained from the District Health Services Directorate of the Ministry of Health in Ghana, to validate the malaria incidence viewpoints expressed by research participants in the health questionnaires. Subsequently, the conclusions derived from the key informant interviews were employed in the design of a final QCA investigation in CHAPTER 5. Data consisted of a health survey regarding the causal relationships between mangrove restoration conditions and malaria incidence outcomes as reported by residents in the location. The malaria management benefits of mangrove restoration uncovered in CHAPTER 5 thus reveal any health trade-offs with the fundamental aim of restoration, being environmental conservation. Finally, the theoretical basis of uncovered causal relationships is applied to current malaria management regimes in Ghana, to identify opportunities for policy improvement towards better, more equitable public health outcomes.

[2] Preferred Reporting Items for Systematic and Meta Analyses (PRISMA), an evidence-based systematic review reporting system

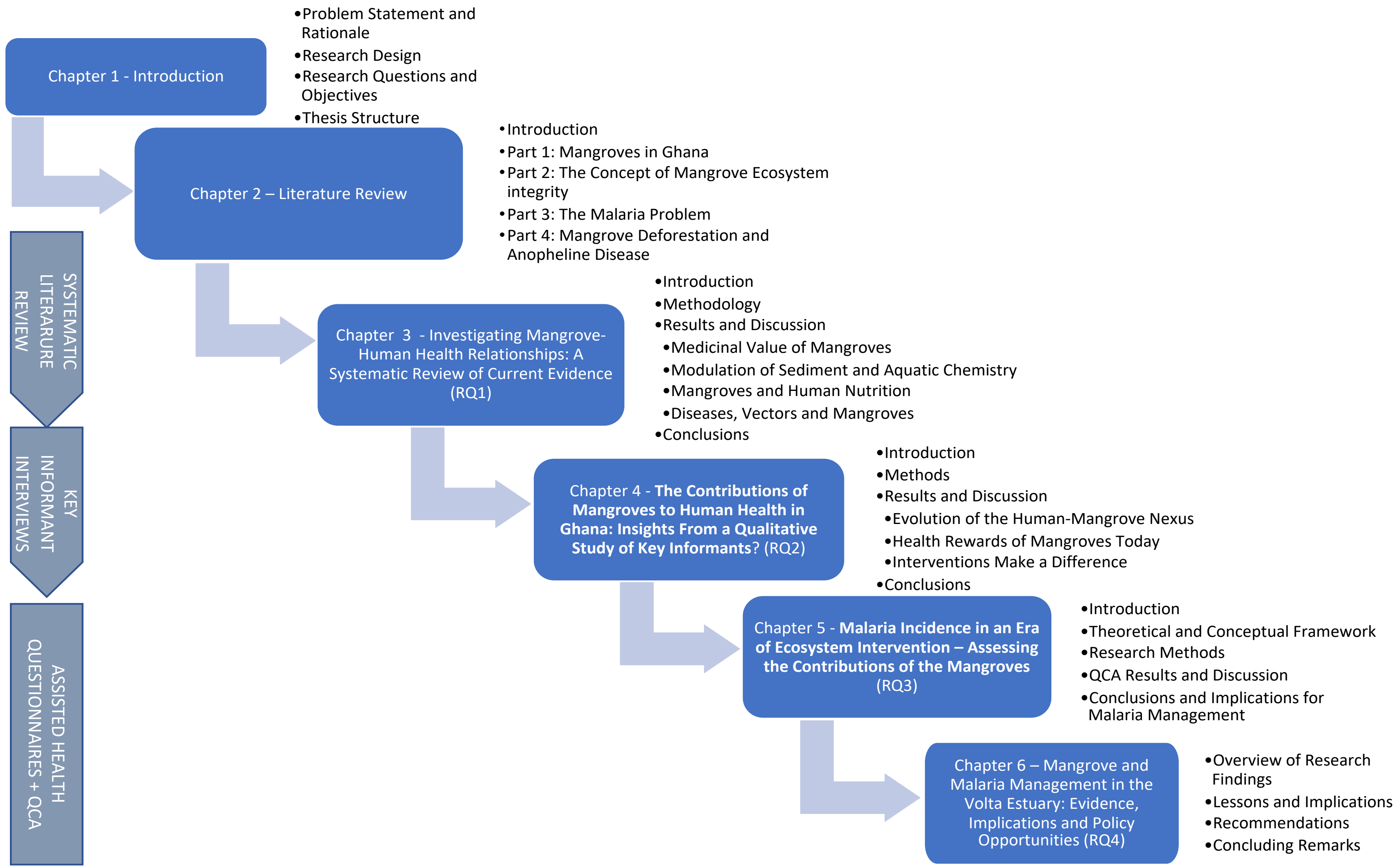

Figure 2: Overall thesis structure. Main chapters are represented in blue, whereas respective methods used are indicated to the left in grey.

CHAPTER 2: LITERATURE REVIEW

2.1 PART ONE – MANGROVE ECOSYSTEMS IN GHANA

2.1.1 INTRODUCTION

Mangroves are trees that inhabit tropical and sub-tropical littoral regions spanning across over 100 countries. They are halophytes[3] that grow in fine organic-matter-rich sediment separated from high energy wave action. The term 'mangrove' can either be used to refer to the plant species that are adapted to mangrove swamps, or to the ecosystem formed by this type of woodland along with the biomes they support. The latter designation is also referred to as 'mangal' (Hogarth, 1999).

Mangrove ecosystems are usually dominated by the tree species, which interact with each other and their physical environment. They have special properties enabling them to cope with the intermittent tidal deluge, hypoxia[4] and elevated salinity that pertain in intertidal environments. Their specialised porous root tissue is adapted to trapping and transport of atmospheric gases, while impermeable suberised[5] roots are competent at salt exclusion. These properties, combined with transpiration-restricting abilities as well as viviparity[6], equip mangrove vegetation to cope with brackish conditions (Teas, 2013).

Close to 50 true mangrove tree species are known (40 in the Indo-West Pacific region and 8 in the western hemisphere) (Tomlinson, 2016). Local mangrove proliferation depends on the continued existence of suitable ecology. In addition to sea-level rise, vulnerability to anthropogenic interferences (extremes of soil/landscape condition, eutrophication and pollution-related water quality, vegetation removal, introduction of invasive species, etc.) have significant effects on how well tropical mangrove ecosystems develop and survive (Osland et al., 2016). Establishment is additionally contingent on how easily mangrove propagules can colonise their surroundings. Water diversions that distort natural freshwater flow systems, and thus salinity and nutrient supply patterns, are also major impediments to mangroves (Chapman, 1976).

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[3] A plant adapted to growing in saline conditions, as in a salt marsh.
[4] Deficiencies in available oxygen.
[5] Impregnated with suberin, an inert waxy substance that confers impermeability.
[6] Offspring developing while still attached to parent.

Mangrove ecosystem resources have been useful to tropical coastal dwellers for millennia (Saenger et al., 1983). Their importance as wood sources, nursery grounds for fisheries, wildlife habitats, water quality improvement systems and coastline protectors has been abundantly documented (Saenger, 2013). These direct goods and services sustain nearby communities, where the often-subsistent nature of economies means that livelihoods and wellbeing are threatened under ecosystem degradation or restricted or access. Kinds of goods and services supplied by local mangroves however depend on peculiar factors such as vegetation type, biodiversity and ecosystem conditions resulting from management regimes and resource exploitation patterns.

2.1.2 NATURE OF GHANA'S MANGROVES

2.1.2.1 Distribution

The Ghanaian coast stretches over a 550 km area (Tsikata et al., 1997). There are six agro-ecological zones, namely Sudan Savannah, Guinea Savannah, Coastal Savannah, Forest/Savannah transitional zone, Deciduous Forest zone and the Rain Forest zone (moist and wet evergreen) (FAO, 2010). Mangroves occur only along the coastline lagoons and estuaries of major rivers of the coastal savannah and southernmost wet evergreen zones (Figure 3 and Figure 4). Although GIS technology has found widespread use in geographical mapping, its application in mapping mangrove resources in Ghana has been limited. This creates a challenge in the availability of reliable data for the assessment and management of mangrove ecosystems. One such rare study conducted by Agyeman Boakye et al., (2007) on what they termed 'sub-ecological zones' of the country, estimated total mangrove cover to be in the region of about 112.6km2 (Table 1). Mangroves are sparsely distributed in Ghana, with the most mature ecosystems located in the low-lying region between Cape Three Points and Côte d'Ivoire in the Western Region, whose lagoons make up 10% of the total surface area. A secondary less developed mangrove-growing region can be found along the fringes of the lower Volta estuary (Corcoran et al., 2007) where the case study sites of this research are situated.

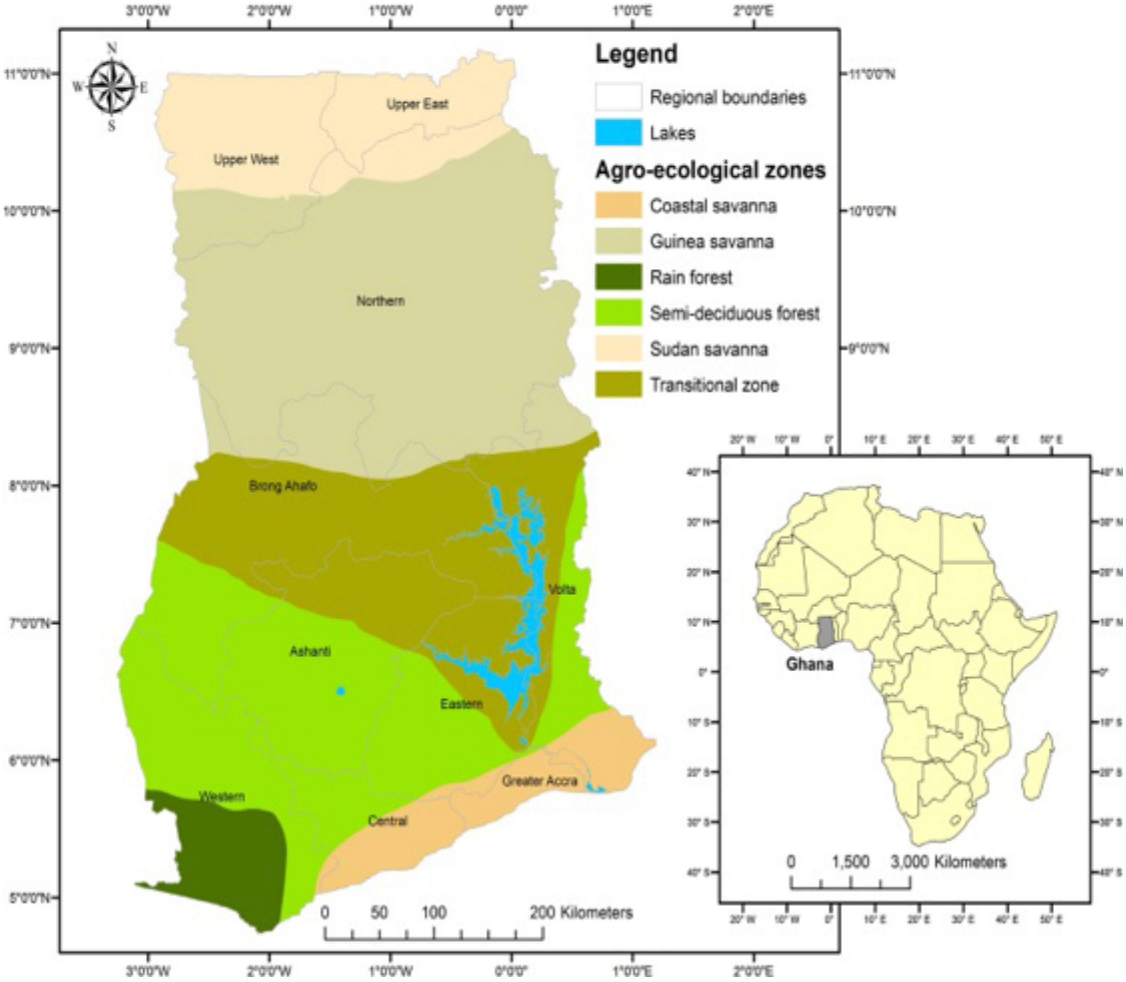

Figure 3: Agro-Ecological Zones of Ghana (Rhebergen et al., 2016)

Table 1: Estimated Mangrove Areas within the Sub-Ecological Zones of Ghana (Agyeman et al., 2007)

ECOLOGICAL ZONES	ESTIMATED AREAS (km^2)
Wet Evergreen	26.2
Moist Evergreen	30.12
Moist Semi-Deciduous	0.76
Dry Semi-Deciduous	0.02
All Savanna	51.84
Southern Marginal	3.70
Upland Evergreen	0.00
Total Estimate	112.64

2.1.2.2 Biodiversity and Ecological Significance

Species diversity of mangrove vegetation in Ghana is extremely limited. The three dominant species are *Laguncalaria racemosa*, *Rhizophora racemosa* and *Avicennia africana* (Wilkie and Fortuna, 2003; Sackey et al., 1993). Endemic mangrove species have sometimes been described as components of an ecological mosaic, within which they are interspersed with one or two populations of shrubs, ferns, and palms (Agyeman et al., 2007). They dominate, and form concentrated or scattered patches, with dense canopies and varying heights of stems and stilt roots. Other mangroves are on the average more stunted than those found in the 'wet and moist evergreen' and the 'far-eastern savannah' mangroves found in the Western and Volta regions respectively (highlighted yellow in **Figure 4**). The authors also suggest that these two regions harbour the highest concentration of mangroves in the country, with heights of between 5m and 10m above ground and tree trunk diameters of between 5cm and 30cm. Day et al., (2018) suggest that differences occurring within the tree communities in tropical mangrove ecosystems draw from the diversity in abiotic conditions, specie content and the nature of the land.

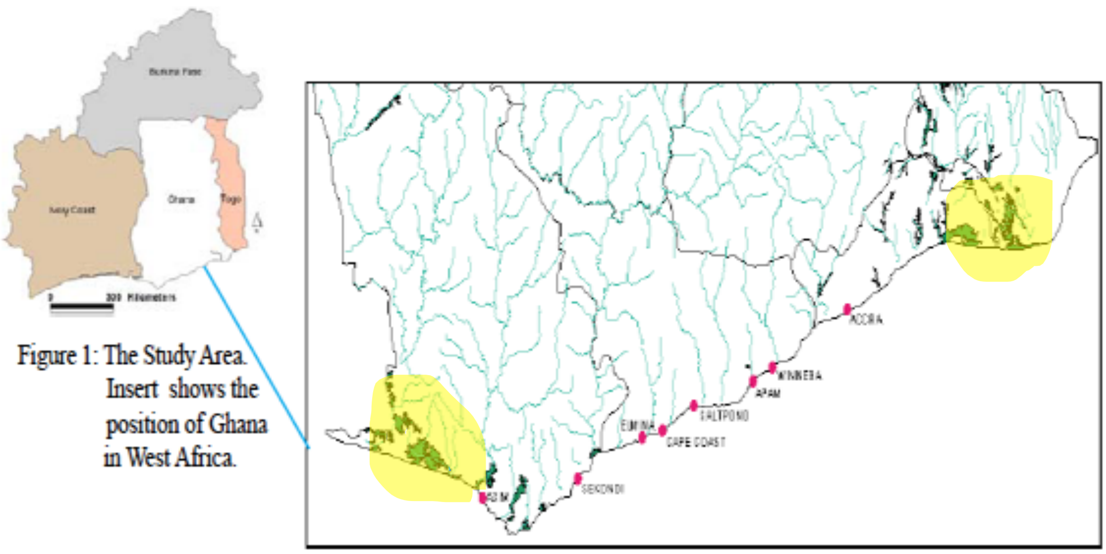

Figure 4: Mangrove locations along Ghana's coast (Coleman et al., 2004), with major settlements and waterbodies indicated in pink and green, respectively. The area shaded yellow to the left harbours the most mature mangrove vegetation, whereas the Volta Estuary (shaded yellow to the right) has the most expansive forests.

Despite having previously been undervalued and categorised as 'wastelands' (DasGupta and Shaw, 2013), acknowledgement of the importance of mangroves and thus the need for further research has increased in recent times. Insights into the richness of the food webs and biodiversity they support have led to their characterisation as one of the most productive ecosystems worldwide (Dahdouh-Guebas, 2002). Many ecologists now recognise mangrove ecosystems as highly beneficial systems for human wellbeing, with major ecological roles including but not limited to the following:

1. Sediment regulation/soil formation and coastline stabilization (Woodroffe et al., 1992)
2. Carbon sequestration (through biological productivity and biogeochemical activity) (Chmura et al., 2003)
3. Water quality improvement though filtration of upstream run-off (Lawson, 2011; Ajonina, 2008; Din et al., 2008)
4. Habitat and refuge for aquatic and peri-aquatic species (Spalding et al., 2010)
5. Production of food web-supporting detritus and other food sources (Egnankou Wadja, 2009; Alongi, 2011)
6. Coastal storm protection (Raulerson, 2004; Crona et al., 2009)
7. Spawning and nesting location for many aquatic species and migratory birds (Marquette et al., 2002; Ntiamoa-Baidu and Gordon, 1991)
8. Recreational and ecotourism sites (birdwatching, recreational fishing, snorkelling, canoeing etc.) (Barbier et al., 2011)

The vast ecological benefits obtained for mangroves make them a crucial environmental resource. In Ghana they offer coastal storm protection, support habitats, act as spawning grounds for numerous aquatic species and supply nutrients to others. Many marine species use mangrove swamps for spawning and nursing their young. The stilts of the mangrove vegetation, along with the shallow waters in which they reside, makes them an ideal ecological formation for juvenile aquatic species especially, to seek refuge from predators (Wilkie and Fortuna, 2003). Detritus[7] from mangrove ecosystems is a vital nutrient source for benthic[8] micro and macrofauna, which in turn serve as food for

[7] Particulate organic matter and their attached microorganisms
[8] Occurring at the bottom of a water body

near-shore crustaceans, fish, and shellfish (Odum et al., 1973). Fish-dependent livelihoods and nutrition are thus intricately linked to mangrove ecosystem health. Mangrove stands also control the rate of sediment deposition, with their nutrient transforming and pollutant removing properties preserving habitat health for a vast array of animal biodiversity (Manson et al., 2005; Wilkie and Fortuna, 2003). Mammals, reptiles, amphibians, and bird are some groups of such organisms, some of which are often endangered (Nunoo and Agyekumhene, 2014).

Unique megafauna such as birds, frogs, toads, salamanders, manatees, monkeys, and various invertebrates feed within and find shelter in the mangrove ecosystems of coastal Ghana (Ntyam, 2014). Some notable fish varieties the writer documents include *Periophthalmus papilio* (the mudskipper), *Caranx hippos, Liza* spp, *Tilapia guineensis* and *Sarotherodon melanotheron.* Also recognised are mollusk species including *Ostrea rhizophorae* and *Littorina angulifera.* Crustaceans found are crabs, like *Cardiosoma armatum and Uca tangerii.* Turtles have long been mangrove dwellers in Ghana, with *Chelonia mydas*, *Dermochelys coreacea* and *Caretta caretta* being the endemic species. Several species of plovers, egrets, waders, terns, and herons also find homes among Ghana's mangroves (Ntyam, 2014).

2.1.2.3 Socio-Economic Importance

Due to immense contributions to livelihoods, mangrove use has been identified as an important and beneficial economic activity within the West-Africa sub-region (Feka and Manzano, 2008; Ajonina and Usongo, 2001). Mangal wood is used as fish stakes, for building construction, as agricultural inputs (e.g., for staking yam and tomato plants) and as fuel for various activities in Ghana (Macintosh and Ashton, 2003). Ayisi and Addo (1994) additionally acknowledge widespread exploitation of endemic mangrove tree species for charcoal making, firewood and fish-smoking in the country.

The ecological significance of mangrove ecosystems in safeguarding the profitability of the fishing industry in nearby settlements is also a vital one. This is because of the status of fish as the most important protein source in Ghana, which consequently makes fishing a very lucrative economic activity for communities (Aggrey-Fynn, 2001). Dependence on fishing is of such critical importance that for fear of income losses, some fishers are willing to defy health warnings conveyed in safety directives of monitoring authorities about fishing from polluted lagoonal waters (Bentum et al., 2011). In the absence of access to mangrove resources therefore, livelihood strategies and nutritional needs stand to be negatively impacted.

2.1.3 STATE OF MANGROVES IN GHANA

Mangroves of the Gulf of Guinea where Ghana is situated were once regarded as the fourth most vulnerable ecosystems globally (Ukwe et al., 2006), due to absence of strategic management policies for their protection unlike in regions like Asia (FAO, 1994). According to the FAO (2010), mangrove losses across the coastline of West Africa exceeded 250,000 ha[9] between 1990 and 2010. Exploitation of mangrove resources in this region has been facilitated by land tenure systems that favour community and individual control (Kumi et al., 2015). Moreover, coastal vegetation management has not been adequately covered in any stringent legislative framework which absolutely guarantees sustainable use (Asante et al., 2017). Therefore, lands under government and family protection enjoy restricted access, whereas communal lands are more likely to be overexploited and misused. Although various monitoring and restoration projects have been documented in the sub-region, a net reversal in degradation trends is yet to be observed. A 25-year review of West African mangroves carried out by the FAO identified rapid urbanisation (settlement extension) and mangrove land conservation for agricultural purposes (e.g., shrimp ponds, rice paddies, salt mining etc.), as the primary threats in the sub region (FAO, 2007). A more recent UNESCO policy brief and similar studies agree on this (Van Lavieren et al., 2012), but variations exist in the main drivers of mangrove degradation at country levels.

Two main reasons for mangrove decline are mangrove habitat loss and overexploitation of forest resources. Studies have revealed that in Ghana's unique situation, a 24.3% decrease in mangrove vegetation cover occurred between 1980 to 2006 (Abe et al., 2000; Corcoran et al., 2007). These studies also reveal how economic activity drives

[9] Hectares

conditions that promote mangrove decline. The boom in economic activity that accompanies population growth in nearby settlements has facilitated exploitation of mangrove resources. Unfortunately for Ghana, because of the convenience of easy access to shipping hubs, most economic activities that bolster the national economy are located around the coast. Up to 90% of all industries, for example, are found in coastal regions (Abe et al., 2000). This leads to coast-oriented rural-urban migration and thus population growth in those areas, which also happen to harbour the country's mangrove-supporting wetlands.

Lagoonal and estuarine mangroves, as occur in Ghana, are found in low wave energy locations, and require periodic extensive flooding to disperse their large propagules (Richards, 1996a). Hydroelectric damming of the Volta River at Akosombo and Kpong, in 1964 and 1975 respectively, is argued to have heavily influenced mangrove habitat loss in the Volta estuary. Although the resultant electrification has been the backbone of development in the country, these events led to a systematic and progressive decline in downstream flow into the Volta Estuary. This development heavily impacted the habitat recolonization ability of the principal mangrove species, *Rhizophora racemosa*. The scenario continues to interfere with successful distribution of propagules, and further supports colonisation by competitive weeds that rapidly take up potential mangrove substrate. Rubin *et al.*, (1999) report how the lack of flooding causes the seedlings to become wedged in mud, where they are easily accessible to the sesarmid[10] crabs that consume them. Agriculture collapse and reduction in fish yields, also consequences of the limited downstream hydrologic flows, instigated mangrove cutting for firewood and fish smoking as additional livelihoods (Tsikata et al., 1997). Unfortunately, mangrove wood harvesting compromises the ecosystem, making it unsuitable for proliferation of fish populations, leading to further fish yield reductions in a negative feedback mechanism that drives even greater mangrove exploitation (Figure 5).

[10] Of the family Sesarmidae. Members need not return to the sea even for breeding.

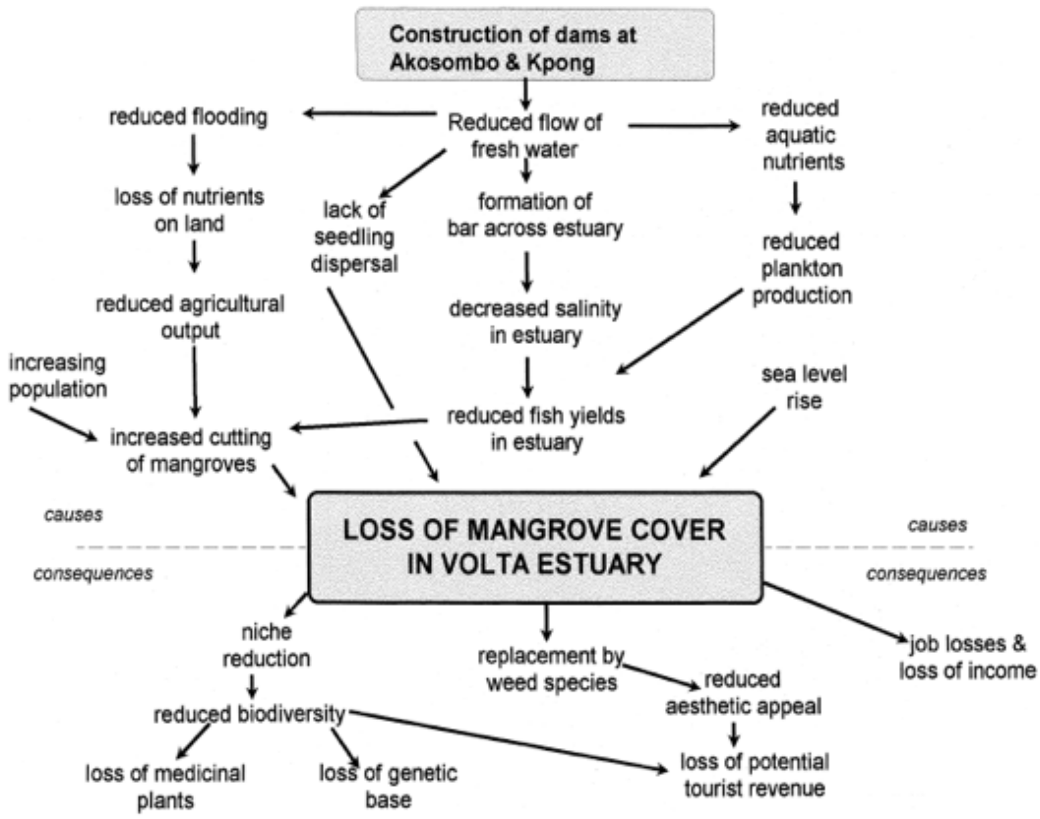

Figure 5: Causes and Consequences of Mangrove Loss in the volta Estuary by Rubin et al., (1999) after Qureshi, (1996)

Corcoran et al., (2007) also acknowledge, in addition to the dams, the role played by dykes and seawalls in overall mangrove decline in the region, with a widely accepted scientific backing for these phenomena (Rubin et al., 1999). Land use conversions for agricultural purposes also bring about progressive deforestation, which opens these areas up to more extensive environment related threats to wellbeing. Storm surges damage crops and property in mangrove absence, and there is evidence of impacts on disease incidence and distribution as well (de Souza et al., 2010).

While mangrove ecosystem degradation involves over-exploitation of goods and services beyond just wood harvesting, the logging of mangrove wood often instigates more extensive ecosystem degradation. Feka (2011) contends that mangrove wood harvesting catalyses the exposure of many mangrove ecosystems to further depletion of their other resources. The argument is made that wood harvesting invites complex alterations in the dynamics of the mangrove ecosystem (forest structure, make up and regenerative ability). Longonje and Raffaelli (2012) mention how even relatively small-scale logging can adversely affect mangrove ecosystems integrity if done in an unsustainable manner, especially where other threats to the habitat are also at play. This is one reason restoration of mangrove woodland through replanting becomes demonstrative of the return to a replenishing pathway for a degraded mangrove ecosystem.

Rehabilitation of mangrove ecosystems damaged by wood harvesting is usually synonymous with replanting of rapidly growing and economically relevant mangrove tree species (Field, 1999). The replacement of tree cover prevents considerable changes in soil and water conditions (Richards, 1996a), thereby making room for a reversal of degeneration within the ecosystem. Considering the difficulties that exist for natural mangrove recolonization in the face of hydrological stresses imposed by the Volta River dams, replanting alone does not offer permanent rehabilitation. If the replanted mangroves are, like their predecessors, likely to face difficulties propagating from one generation to the next by default, anthropogenic drivers of mangal deforestation must be tackled to eliminate that additional ecosystem stressor following revegetation.

2.1.4 MANGROVE ECOSYSTEM MANAGEMENT IN GHANA

For a long time, Ghana's wetlands were regarded as 'wastelands' that were undesirable because they allegedly "bred mosquitoes." They often were used as refuse disposal sites, dredged for drainage, or simply reclaimed for other uses considered to be more beneficial (MoL&F, 1999). Arbitrary harvesting of material from wetland resources like mangroves was therefore widespread. The signing of the Ramsar Convention in 1988 brought with it the attempt to reverse these trends. Although the government retains the oversight social, economic, and environmental responsibility for mangrove habitat management within Ghana's wetlands, indigenous communities in the first instance are considered directly responsible for ensuring that resources within such locations are used wisely.

2.1.4.1 Informal Sector

Key actors in sustainable mangrove management in the country have been Ghana's Forestry Commission (consisting of the Wildlife Division and the Forest Services Division) and the Forestry Research Institute. These primarily promote sustainable use of forestry sources, forestry research, as well as development of technologies for regenerative silviculture among others in consultation with local community stakeholders. The informal sector also contributes significantly to local knowledge and practices in the form of customary laws and taboos that govern resource use at the grassroots level (Corcoran et al., 2007).

The traditional framework for wetlands protection has been extended from indigenous management practices, which are varied depending on the location and the land ownership rights in place. These practices are collectively accepted as a regulatory mechanism strengthened by the instigation of sanctions for disruptive behaviour by the appropriate local authority where necessary. Some studies like Darkwa and Smardon (2010) revealed that a heavy percentage of respondents in rural communities consider their cultural beliefs, practices, and knowledge as major influences on how they use nearby lagoons and their resources. They report that proverbs, myths, and legends (of a supreme being and his lesser gods as custodians of natural resources) are some mechanisms through which local ecological knowledge is translated into sustainable practices.

Traditional management practices that contribute towards resource conservation include fishing taboo days, periods of prohibited fishing, forbidden farming inputs and observation of fallow periods among others (Koranteng et al., 2000). These customs in concert make room for regeneration of fisheries, wetland, and forest resources through restrained consumption over time. Their effectiveness has been demonstrated in studies that show how tabooed species flourish in areas where proscriptions regarding their collection are in place. Ntiamoa-Baidu (1991) for example, reported how black herons and the water snail *Tympanotonus fuscatus* species were between 800 to 4000 times more abundant in the Sakumo lagoon area than anywhere else in Ghana due to indigenous prohibitions.

At the community level, inhabitants have initiated several mangrove restorations projects. Aheto et al., (2016) report on the importance of community initiatives in the attainment of restorative success in mangrove ecosystems in the Volta Estuary in Ghana. They express how the tailor-made socio-economic and ecological objectives of community-based management programs have led to greater success in that region for over twenty years, making projects of such nature a viable alternative to externally initiated ones. Unfortunately, some externally initiated restoration projects fail to incorporate local ecological knowledge into their planning, leaving nearby inhabitants feeling side-lined. Threats of exploitation and land use change remain, and the knowledge gaps relating to local governance issues that impinge upon decision-making at the grassroots level are likely to undermine restoration initiatives within mangrove lands (Beresnev et al., 2016).

2.1.4.2 Formal Sector

Ghana lacks express mangrove-protective legislation like it has for terrestrial forest reserves, but policies and strategies exist for general wetland management (Macintish and Ashton, 2005). A few policies exist that have bearings on wetland usage, and some have sometimes been enacted into law. Notable among these are the Fisheries Law (a 1972 decree), Environmental Policy, Medium-Term Development Policy (Vision 2020), Water Resources Commission Act (522), Wildlife & Forestry policy and the Land Policy (MoL&F, 1999).

As part of the 1999 National Land Policy aimed at ensuring judicious use of all land-related resources, wetlands were acknowledged as requiring conservation along with the adoption of some prohibitive practices. Activities like drainage of wetland water, waste disposal and human settlements were restricted within these areas in a National Wetlands Conservation Strategy that was updated in 2007 (Ramsar, 2014a) .

Other related devices include the Coastal Zone Management Indicative plan, the Integrated Coastal Zone Plan, and the National Wetlands Conservation Strategy & Action Plan. These have collectively led to various restoration and conservation projects (Asante et al., 2017). Some of such projects as reported in Feka *et al.*, (2014) are highlighted in Table 2 below.

With Ghana's 1988 ratification of the Ramsar Convention on Wetlands came the categorisation of some vulnerable wetlands as 'Wetlands of International Importance', and their subsequent earmarking for preservation and rehabilitation. The country's commitments thereof necessitated the designation of mangal habitats as protected areas according to the Ramsar obligation of 'wise use' (Ramsar, 2001). There is the hope also, that mangrove conservation would significantly feature in the policies and strategies emanating from Ghana's UNFCCC[11] and REDD+ [12] commitments.

2.1.4.3 Mangrove Rehabilitation Efforts

The practice of replanting and strategically harvesting mangroves is new in West Africa, having emerged at the turn of the 21st century. In Asia however, such practices have been reported for centuries (Kairo et al., 2001). Because of the complex nature of the reproductive ecology of mangroves, it is important to investigate and address all biotic and abiotic stressors of a particular mangal habitat to ensure replanting success (Tomlinson, 2016; FAO, 1994). A few restoration initiatives have been accompanied by regulation of access to the sites to reduce anthropogenic interferences. They exploit the impeccable ability of mangroves to recover from disturbances provided propagules are abundant and disruptions are not recurrent (Tomlinson, 2016). Sometimes replanting is successful when non-mangal species have been separately included as an alternative source of wood for dependent settlements (Feka et al., 2014).

Community participation is imperative to the overall success of such initiatives, as it generates a sense of ownership and desire to comply with well-intentioned sustainable management directives (Bosire et al., 2008). Alternative livelihood solutions are key to eliminating anthropogenic stressors that hinder regeneration attempts. According to Robinson et al., (2011) supplementing replanting projects with economically beneficial initiatives such as ecotourism helps such projects to be better received and supported by the wider community. Mangrove-dependent communities restricted form accessing replanted mangrove territories often rebel against forcefully implemented conservation

[11] United Nations Framework Convention on Climate Change
[12] Reducing Emissions from Deforestation and (Forest) Degradation

strategies. They view such initiatives as a violation of cultural values and are frequently in conflict with the dysfunctional state institutions which rarely succeed without community consultations (McClanahan et al., 2005; Wiegal et al., 2011). Community-initiated and agreed restoration approaches thus hold better promise.

Local and international NGOs[13] as well as international governmental aid agencies such as the GEF[14] and The International Tropical Timber Organisation have diversely partnered Ghanaian agencies in research and delivery of conservation projects centred on mangrove management. Some of these projects are highlighted in Table 2.

[13] Non-Governmental Organisations
[14] Global Environmental Facility of the World Bank

Table 2: Examples of Recent Formal Coastal Wetland Management Projects in Ghana

Project Name	*Funding Agency*	*Implementing Agency*	*Focus Area(s)*	*Description*	*Results*
Mangrove Restoration/Tree planting for Biodiversity and Sustainable Management of Wetland Resources, Adzato Community, Keta Lagoon Ramsar site	Rufford Foundation	Martin Ahorbo (Grant awarded for independent research)	Conservation: Reforestation	Public awareness creation, educational workshops, and raising and planting of mangroves and tree seedlings in Keta Lagoon Complex	Public awareness objective partially fulfilled; objectives for tree planting, workshops, training fully accomplished
Biodiversity Threats Assessment for the Western Region of Ghana: Integrated Coastal and Fisheries Governances Initiative	USAID	Coastal Resources Center, University of Rhode Island; in partnership with: The Government of Ghana, Friends of the Nation, SustainaMetrix, and the WorldFish Center	Coastal and marine governance; fisheries; community outreach and capacity building; biodiversity; conservation; sustainable livelihoods	Initiative addresses six key challenges: creating a coastal and marine governance program for the Western Region; addressing fisheries governance issues in the region; improving the governance of coastal resources in the focal areas of Shama District, Cape Three Points and the Amanzule Wetlands and undertaking a major communications, outreach, and capacity building effort	Phase I implemented in 2009-2010. Following mid-program self-assessment, (2011), key anticipated outcomes included working models of best practices in integrated coastal management, including examples of community-based approaches to fisheries management operational at the local scale; policy proposals for a novel approach to both ICM and fisheries governance nested within national policy frameworks and that support local level actions at the district and community scales. Documentation of focal area and district-level efforts found here
Sustainable community management, utilization, and conservation of mangrove ecosystems in Ghana	ITTO (funded by USA, Bali Partnership Fund); Government of Ghana	Sustainable livelihoods; resource management; biodiversity; conservation	Sustainable livelihoods; resource management; biodiversity; conservation	Project intends to identify opportunities and threats to sustainable management, utilization, and conservation of mangroves by local communities	Policy and legislative guidelines for community-based mangrove management formulated; current state and economic importance of mangroves in Ghana assessed; security of tenure, institutional arrangements, and governance to empower local communities in mangrove management and decision-making strengthened; and project proposal on sustainable management, conservation, and utilization of mangroves by local communities in Ghana formulated and submitted.
Community Mangrove Restoration and Sustainable Utilization of Natural Resources within the Muni-Pomadze Ramsar Site, Ghana	GEF Small Grants Program	ARocha Ghana	Sustainable livelihoods; biodiversity; conservation	Project aims to restore the ecological integrity of the Muni lagoon and adjacent traditional hunting grounds through local capacity building; implements conservation education programs, training of communities, proper demarcation, and mapping of site boundaries to enhance law enforcement and resource protection and rehabilitation of degraded	Project Completed

Project Name	*Funding Agency*	*Implementing Agency*	*Focus Area(s)*	*Description*	*Results*
Ecosystem-based adaptation practices to rehabilitate degraded mangroves to protect marine turtles and prevent sea erosion within the Songor Ramsar Site	Biodiversity and Ecological Restoration Committee	Biodiversity and Ecological Restoration Committee	Sustainable livelihoods; conservation; restoration; reforestation; biodiversity; eco-tourism	Project intended to restore degraded mangroves to protect nesting turtles and other endangered wildlife species through collaborative efforts to promote ecotourism and sustainable livelihoods; aims to rehabilitate 30 ha of degraded mangroves through the planting of 15,000 mangroves and 10,000 other appropriate tree seedlings and species; awareness campaigns conducted in 30 schools and 20 communities	Project Satisfactorily Completed
Integrated Management of immature Mangroves to Rehabilitate the Degraded Abakam-Elimina Coastal Wetlands and Ramsar Sites in the Central Region	GEF Small Grants Program	Rural Action Foundation	Sustainable livelihoods (aquaculture); biodiversity; reforestation; conservation	Project aims to contribute to the restoration of coastal, marine, and freshwater ecosystems of the southern dry margins; creates community awareness of economic potential of mangroves and aquatic weeds; builds local capacity for mangrove restoration and sustainable wetland management; promotes compost production and cage aquaculture as rural enterprise	Satisfactorily completed: Two demonstration farms established for compost; seven project management teams formed and trained on cage aquaculture; 50 manuals on cage aquaculture and compost production produced and distributed; three groups of 30 formed to embark on goat rearing.
Eco-Health Approach to the Control of Onchocerciasis in the Volta Basin of Ghana	DFID and IDRC through the CCAA program	University of Ghana (Noguchi Memorial Institute for Medical Research)	Capacity building; research; public health	Project used ecosystem approaches to human health to investigate how climate change will modify current onchocerciasis transmission patterns in the Volta Basin	The scope of work included field visits to hydro-meteorological observatory stations in the Pru and Black Volta basins, analysis of trends in extreme climate events, pre-processing of various data for modeling, initial set up of the hydrological model SWAT (Soil and Water Assessment Tool) and training of Graduate students in hydrological modelling
Climate Change and Human Health in Accra, Ghana	IDRC	Regional Institute for Population Studies	Research; public health	Examination of the interactions between deterioration of the rural environment, rural to urban migration, urban slums and	Project successful but with delays; slow government response; impacts measured for awareness campaign,
Community-based Integrated Coastal Zone Management for enhanced agricultural biodiversity and improved rural livelihood in Amlakpo, Adodoajikope, Asigbekope and Kenya in the Dangbe East District	GEF Small Grants Program	Climate Change Mitigation International Waters Land Degradation	Sustainable livelihoods; biodiversity; conservation; reforestation	Project aims to contribute to the conservation of biodiversity and sustainable coastal zone management in Songor Ramsar sites in Dangbe East District; specifically, enhances the capacities of cooperative groups in Amlakpo, Asigbekope, Kenya and Adodoajikope.	Satisfactorily completed. Ramsar sites fully protected, traditional policies for reversal of over-exploitation and degradation enforced, monitoring system implemented, multi-purpose woodlot established, alternative livelihoods and agricultural skills transfer applied.

2.2 PART TWO – MANGROVE ECOSYSTEM INTEGRITY

2.2.1 WHAT IS ECOSYSTEM INTEGRITY?

Decision-making on ecosystem management, whether for biodiversity conservation or other human welfare related motives, relies on measures of desirability within ecosystems. This measure is what writers like Smyth *et a*l., (2007) and Burkhard & Muller, (2008) have described as the classification of the 'Ecological Quality' of an ecosystem. Steyaert and Ollivier, (2007) expressed how this idea gained prominence, especially with its adoption as a critical benchmark in contemporary changes to certain legal frameworks. Most assessments on ecological quality however tend to be predisposed along the lines of what the motives of the evaluators are (Paetzold et al., 2009). A climate scientist, therefore, may be more interested in an ecosystem's capacity as a carbon sink, whereas a conservationist may concentrate on specie-diversity within it. A more definitive and consistent model of what constitutes ecological quality is therefore necessary, if decisions based on its measure are to be unanimously accepted.

Woolsey *et al.*, (2007) emphasize how public acceptance of policy hinges on the elimination of all potential biases in how we arrive at what is important in the assessment of ecological quality. In the continued quest for a more robust definition of ecological quality, there have been a few related concepts explored within academia. Notable among such spin-offs are Karr's (1999) 'biological integrity' and Rapport's 'ecosystem health' theories (Rapport et al., 1998). The research fraternity is however divided on the utility of these concepts and their theoretical basis (Lackey, 2001).

Rapport's definition of ecosystem health, for example, is pivoted around sustainability, organization, autonomy, and resilience; and requires healthy ecosystems to experience no organisational and functional changes across time and space. Operationally such a state is difficult to attain and measure, as it would involve a definitive description of what constitutes an optimal or target state for all constituent aspects of ecosystem structure and functioning. Such descriptions tend to vary based on the interests of the assessor as well as the reliability of the reference data available. The constraint in achieving precision and consensus in this regard limits the expediency of this concept (Lancaster, 2000).

In like manner Karr's biological/ecological integrity concept is based on how close an ecosystem's state is in comparison to 'natural' habitats in terms of functioning, species diversity and composition. Parrish *et al*., (2003) present ecological integrity as a measure of an ecosystem's composition, structure, and function as compared to its natural or historical range of variation in the face of natural and anthropogenic change. 'Natural' as used in this context refers to a situation where human influence is completely excluded, with the ecosystem perceived to be closest to a natural state considered to have the highest integrity (Tierney et al., 2009). The key determinants of this measure are ecosystem composition, structure, and function. This designation of ecological integrity (used interchangeably with the term 'ecosystem integrity') has been favoured by some environmental legislation like the European Union Water Framework Directive (Lackey, 2001). The difficulty associated with this definition lies in its reliance on the necessarily equivocal notion of what is 'natural', a consensus that is almost impossible to attain. Foley *et al*., (2005) reiterate this concern through emphasis on how societies' sheer existence place unavoidable demands on all ecosystems for their life-sustaining services. Obtaining reliable reference values of indicators for the purposes of identifying deviations from the normal/natural thus becomes challenging. Surrogate delineations have also been presented on how ecological integrity could alternatively be viewed.

Thermodynamics has been the basis of alternative considerations surrounding the conceptualization of ecological integrity within ecosystems. The working assumption here is that ecosystems have at least one favourable operative condition under which energy conservation and degradation, in the form of solar radiation, are at their optimum (Müller and Burkhard, 2005). As a result, measurable ecosystem characteristics (food webs, connectedness, productivity etc.) are expected to increase while the ecosystem enjoys uninterrupted progression (Müller et al., 2000). This approach is still contingent on what is perceived to be a valuable change within an ecosystem in the context of the aims of an investigation. A rise in fisheries supporting services in a mangrove forest may be more valuable to inhabitants of dependent communities, but governments with greenhouse gas reduction targets may be more fixated on how to enhance its carbon sequestration capacity.

In all these conceptual variations examined, one recurrent theme is the significance of the nature of what constitutes a valuable property of an ecosystem. This resonates with the concept of 'ecosystem services', that focuses on the quality of benefits that humans derive from the proper functioning of ecosystems as the foundation for determining their health and value (MA, 2005; De Groot et al., 2002). When this concept is fused with the assessment of ecological integrity, it becomes apparent that human perceptions of value are key and must be integrated into methodologies, to ascertain which variables are most crucial. Once this has been done, they must be incorporated into the setting of assessment objectives, with the view to facilitating accurate selection of variables that convey the most useful information about ecological integrity. In it is this light that this study relies on local resident viewpoints in assessing mangrove ecosystem integrity changes over time.

2.2.1.1.1 Working Definition

For the purposes of this study, based on the difficulty in obtaining a natural undisturbed mangrove ecosystem site for comparison, and on the ambiguity of what constitutes 'optimal' conditions within the context of the case study site, an adapted definition is assumed. Ecosystem Integrity, as used inside this study is defined as follows:

> ***The progressive improvement in indicators symbolic of desirable ecosystem structure, organization, and function traits as compared to variations of same indicators under degraded conditions.***

In assessing the states of mangrove ecosystems from one community to another, participants in this research are asked to proffer opinions about changes in indicator ecosystem conditions over time, for both degraded and restored locations.

2.2.2 CONTEXT OF INTEGRITY IN REHABILITATED MANGROVE ECOSYSTEMS

The linkages that exist between mangrove ecosystem processes and external drivers presented by the environment hold the key to the identification of relevant ecosystem status indicators. The state of a mangrove ecosystem, in terms of its resilience and sustainability, is subject to both independent and interacting variables. Dynamics imposed by natural weather patterns determine hydrogeomorphology[15], as is the case with other coastal ecosystems (Lugo and Snedaker, 1974). Sea-level rise, precipitation gradients and vulnerability to human interference regulate the extent to which mangrove ecosystems in the tropics can attain maturity (Osland et al., 2016). The effects of these variables create a dynamic environment that can only be tolerated by mangroves if specific mechanisms for surviving ecological deviations are in place. In other words, the maintenance of 'integrity' in mangrove ecosystems is heavily dependent on the agencies that exist for robust resilience amidst natural and anthropogenic stressors.

Mangrove deforestation triggers decline in soil and water properties as well as habitat and species diversity that eventually diminish ecosystem service provision (Masoud and Wild, 2004; Feka et al., 2011; Richards, 1996b). Most rehabilitation of degraded mangrove sites, whether government managed, or community based, are aimed at rehabilitating them to fully (or better) functioning states through revegetation. The driving forces for such projects vary from a desire to prolong the provisioning services of the ecosystem (timber/fuel wood production, fisheries etc.) to the need to protect shorelines from extreme weather among others (Kairo et al., 2001; Primavera, 2005; Saenger, 2013).

Anchor tree species chosen for re-planting projects are often the fastest-growing, most resilient types capable of establishing themselves in new, fragmented, and stressed habitat conditions (Tomlinson, 2016). The genetic effects of limited tree species options on existing gene pools are poorly understood (Iftekhar, 2008). The inter-related

[15] The interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions (Sidle and Onda, 2004)

ecosystem functions of interest influenced by rehabilitation of mangrove ecosystems are of biogeochemical, ecological, and anthropocentric considerations (De Groot et al., 2002). Those that relate to ecosystem structure/organization are plant population structure and landscape configuration. Finally, some relevant abiotic factors considered are temperature, salinity, nutrients, hydrology, and soil properties. These constituents are further discussed in the next section and summarised thereafter in Table 3.

2.2.2.1 Characterisation of Mangrove Ecosystem Integrity Constituents

2.2.2.1.1 Abiotic Factors

Temperature

Mangrove sensitivity to freezing temperatures, which induces a die-back due to hydraulic failure and structural malformations within xylem tissue (Stuart et al., 2007) is absent in tropical climates. This phenomenon, according to Comeaux *et al.*, (2012) is however becoming less of an issue given the elevating effect of climate change on mean temperatures worldwide. The expectation therefore is that the effects of low temperatures, as an abiotic factor influencing mangrove ecological integrity in the case study region is, negligible with the context of this study. Thus, the mangroves growing within the region of interest can be safely assumed to be immune to the adverse effects of freezing temperatures, with no chances of reduced functionality that could otherwise have been present as suggested by Saintilan *et al.*, (2014). Potential impacts of low precipitation on growth, which could be consequential to higher temperatures within the tropics, is a more important consideration in the research scenario (Feher et al., 2017).

Soil Properties

Land surface, hydrology and water quality features determine the nature of soil accrual over time. Closeness to human settlements also constitutes a major factor in the resolution of soil composition, development, and transformation. Critical inundation-induced hypoxia, generated by the fact that water fills up air pockets and all available interstitial spaces, is a characteristic of most wetlands. It has the potential to hinder normal primary microbial activity within soils. The adaptation that mangroves have that allows them to shirk the effects of estuarine hypoxia lies in their unique ability to oxidise the rhizosphere[16] (Youssef and Saenger, 1996). This capability is further regulated by flooding, redox potential, and sulphide conditions (McKee, 1993). Mangroves in general have both below and above-ground root systems, the former being less developed than the latter. Aerial roots are specifically adapted for transferring atmospheric gases to their counterpart root system below ground.

Red mangroves (*Rhizophora sp*.) tend to have prop roots arising from their trunks and branches, respectively. In black mangroves (*Avicennia sp*.) the lack of either of these adaptive prop root types is compensated for by the presence of 'air roots' (pneumatophores) that extend towards the atmosphere from the underground roots beneath the soil surface. Low tides provide the opportunity for these complementary root structures to trap atmospheric gases for transference to the otherwise aerobically stressed root systems within the soil. Anoxia, which is exacerbated by the accelerated decomposition rates within wetland ecosystems, thus becomes less of an issue in mangrove habitats than it is in confined wetland ecosystems (Mitsch and Gosselink, 2015). This is attributable to the tidal flushing in estuarine environments that facilitates dissolved oxygen levels far above critical, so that impediments to periodic tidal inundation processes threaten proper functioning by limiting oxygen dissolution (Lewis III et al., 2016).

Salinity

High salinity in estuaries effectively excludes certain species of plants and creates a niche environment for the specially adapted mangroves. However, hyper salinity resulting from restricted freshwater flushing, limited precipitation and/or elevated evaporation (all attributes of climate-induced mean temperature increase in the tropics) constitute sources of threat within mangrove ecosystems. The salt content of the aquatic environment controls the osmotic pressure gradient between the substrate and the vascular systems of the trees, thereby influencing transpiration levels (Lugo and

[16] The **rhizosphere** is the soil zone around the roots in which microbial biomass is impacted by the presence of plant roots (Rovira et al., 1974)

Snedaker, 1974). As more fresh water becomes available, primary productivity, transpiration and respiration rates are all observed to increase within mangrove vegetation (Scholander et al., 1962). Fortunately, the high salinity tolerance ability of mangroves means that they can thrive even in regions of reduced tidal flooding, but with consequences for other ecosystem parameters such as regenerative ability of propagule-producing vegetation (Rubin et al., 1999).

Nutrients

Accelerated decomposition rates facilitated by the highly productive microbial biomes mangrove ecosystems support means that general nutrient and mineral limitations are hardly present in such environments. This is especially true for estuarine regions where connectors to rivers exist, in contrast to solely ocean-influenced habitats where sediment deposition from land-based weathering is restricted (Feller, 1995). However, an overly nutrient-saturated environment, while convenient for promoting primary production in the vegetation, can in certain instances prove to be less-than-optimal for the sustainability of the environment according to (Lovelock et al., 2009). The writers argue that this detrimental effect of increased nutrient levels lies in the simultaneously diminishing action it has on below ground productivity. Through the development of lower root-to-shoot proportion, root strength and therefore sediment-holding ability and overall mortality are compromised.

Hydrology

Some components of hydrology pertaining to mangrove ecosystems include precipitation, association with oceans/rivers, water composition, sea level variability and water table dynamics, among others. Within fringe coastal ecosystems, frequent inundation is tide-dependent, much different from riverine and basin mangroves that inhabit areas of totally or partially stagnant water (Lugo and Snedaker, 1974). The span, volume and frequency surrounding estuarine inundation are all relevant parameters that regulate hydrologic variability, but for mangroves the eventual degree of stagnancy is of ultimate interest. This is due to the repercussions on salinity, oxygen and nutrient levels as previously discussed; with hypersaline, anoxic, less-connected regions being less habitable for the tree species plus associated flora and fauna (Lewis III et al., 2016).

Water quality, determined by geomorphology of the habitat (Brinson, 1993) controls nutrient constituents, suspended and dissolved solids as well as salt content. The chemical content of surrounding surface run-off, which has implications for the degree of eutrophication experienced and consequently for dissolved oxygen levels, is of significant weight. These water quality aspects, while being vital for the proper ecological functioning in mangrove ecosystems, could also act as potential sources of stress at elevated levels. Anthropogenic influences (e.g., nearby agricultural activity, dam construction etc.) that have a bearing on these factors directly or indirectly impact functioning within the ecosystem.

2.2.2.1.2 Ecosystem Organization

Structure of Plant Population

The differences that occur within the tree assemblages are imposed by variability in abiotic settings, topography, and the mangrove species present. Most communities are characterised by dense, intertwined canopies. This is especially true for *Rhizophora sp*., whose propagules tend to germinate *in situ*[17] leading to dense, overcrowded thickets over time (Rubin et al., 1999). The understories tend to be comparatively bare, composed of prop roots and pneumatophores as well as salt marsh shrubbery (Mitsch and Gosselink, 2015). Riverine mangrove communities, which enjoy regular freshwater flushes, usually flourish better, giving rise to taller and larger stands than their 'scrub[18]' counterparts that dominate flat coastal fringes (Lugo and Snedaker, 1974). Normally, stable, and undisturbed ecosystem conditions maintained over longer periods facilitate larger trees and denser covers. Biotic and abiotic conditions that dictate the viability of propagules would usually drive the overall expansion of the tree population. Krauss *et al*., (2008) discuss how variations in salinity, temperature, and light intensity impact sapling[19] development. Like other plant systems, propagule abundance and optimum habitat conditions determine the emergence of new colonies, along with the uniquely important buoyancy quality that is pertinent to mangroves (Delgado et al., 2001).

[17] In their place of origin
[18] Dwarf forest
[19] Young tree with a slender trunk

Landscape Configuration

The lack of rich diversity in most replanted mangrove forests does not in any way dilute the complexities in land morphology that are attributable to the effects of ecological and anthropogenic considerations. Day *et al*., (2018) suggest that the existence of hydrologic patterns (relative to structure of the landscape) that facilitate propagule dispersal would promote mangrove expansion in most wetlands, especially where the mangroves have strong competitive abilities alongside other marsh vegetation. Erosion and migration, both consequences of storms within coastal habitats, constitute agents of landscape change in fringe mangrove ecosystems that are absent in inland basin mangrove ecosystems (Smith et al., 2009) (See Figure 6 for visualization of types of mangroves). Human interference comes in the form of obstruction of downstream transport and deposition of nutrient rich sediments, which in the case study area arises from dam construction. This environmental modification has the potential to grossly affect connectivity in the mangrove habitat (Kennish, 2001), with dire implications for survival even where the trees are not actively harvested. Mining activities that remove underground stocks (e.g., of hydrocarbons) leave the landscape prone to subsidence and chemical releases that impair habitat integrity and disturb geomorphic sturdiness (Kennish, 2001; DeLaune et al., 1979). The combined result of reduced vegetation or fragmented habitats affect the stability of affected mangrove ecosystems and their surface protective functions (Kadlec, 1990), which serves as a catalyst to more extensive morphological changes.

2.2.2.1.3 Ecosystem Functioning

Biogeochemical Functions

Organic matter production, elevation (substrate/sediment accretion and stabilization) and decomposition (carbon, energy, and nutrient cycling) are the biogeochemical aspects of ecosystem functioning that are influenced by mangrove replanting. These processes are vital for the successful return of ecological functions to the ecosystem (McKee and Faulkner, 2000). Unfortunately, only a few studies have focused on exhaustively investigating the nature of replanting effects on biogeochemistry.

Primary Production

Although primary production[20] variations occur depending on the type of ecosystem in question, Mitsch and Gosselink (2015) suggest that fringe and riverine mangrove ecosystems (see Figure 6 for description) are known for higher productivity. Compared to other tropical rain forests, mangroves tend to have higher primary productivity. Chapin *et al*., (2002) peg the above ground primary production in tropical rain forest at an average of 1.4 Mg ha^{-1} yr^{-1}, whereas that of mangroves is typically thought to be in the region of between 10 to 30 Mg ha^{-1} yr^{-1} (Bouillon et al., 2008). These values, although tentative, are important because of the role that primary production plays in influencing organic matter accretion aspects of elevation gains as described above.

Abiotic factors of seasonal water levels, dissolved oxygen, salinity, and mineral content (phosphorus, nitrogen etc) have effects on the productivity, with phosphorus and nitrogen in particular exerting limiting effects depending on the kind of substrate present (McKee et al., 2002). Naturally, latitudes and the protracted patterns of weather pertaining in a region over time would determine the temperature precipitation variations. High salinity, low precipitation, low dissolved oxygen, and limited connectivity to freshwater are significant climate-related stressors that constrain productivity potential within a mangrove ecosystem (Gilman et al., 2008).

Primary production has been indicated to be higher in newly restored mangrove forests than in natural ones. Reports illustrate that litter production could range between 7 to 14.16 $tDWha^{-1}year^{-1}$ in 7- to 24-year-old replanted stands of monocultured species (Sukardjo and Yamada, 1992; Nga et al., 2005). This high litter production rate was also shown by the investigators to correspond to higher nitrogen and phosphorus content than is observed in natural mangrove forests. It is possible for newly planted stands to attain organic matter productivity like natural sites as early as 6-7 years after replanting (McKee and Faulkner, 2000). Little is known however, about what explicitly happens to this organic matter within replanted ecosystems. Alongi (2002) points out the relevance

[20] Synthesis of organic compounds from atmospheric or aqueous carbon dioxide.

of this information in the judgement of the impacts on food webs and the overall health of restored ecosystems. In natural stands, up to 40% of organic matter is thought to be recycled through the system via decay, while the remainder is either exported or expended by primary consumers (Duarte and Cebrián, 1996). Decomposition rates on the other hand are thought to be much lower in reforested sites than in natural stands (Bosire et al., 2005). With this reported decomposition deficits in replanted ecosystems, it could be deduced that more organic matter might be made available for the support of food-webs and therefore faunal proliferation within such revived ecosystems.

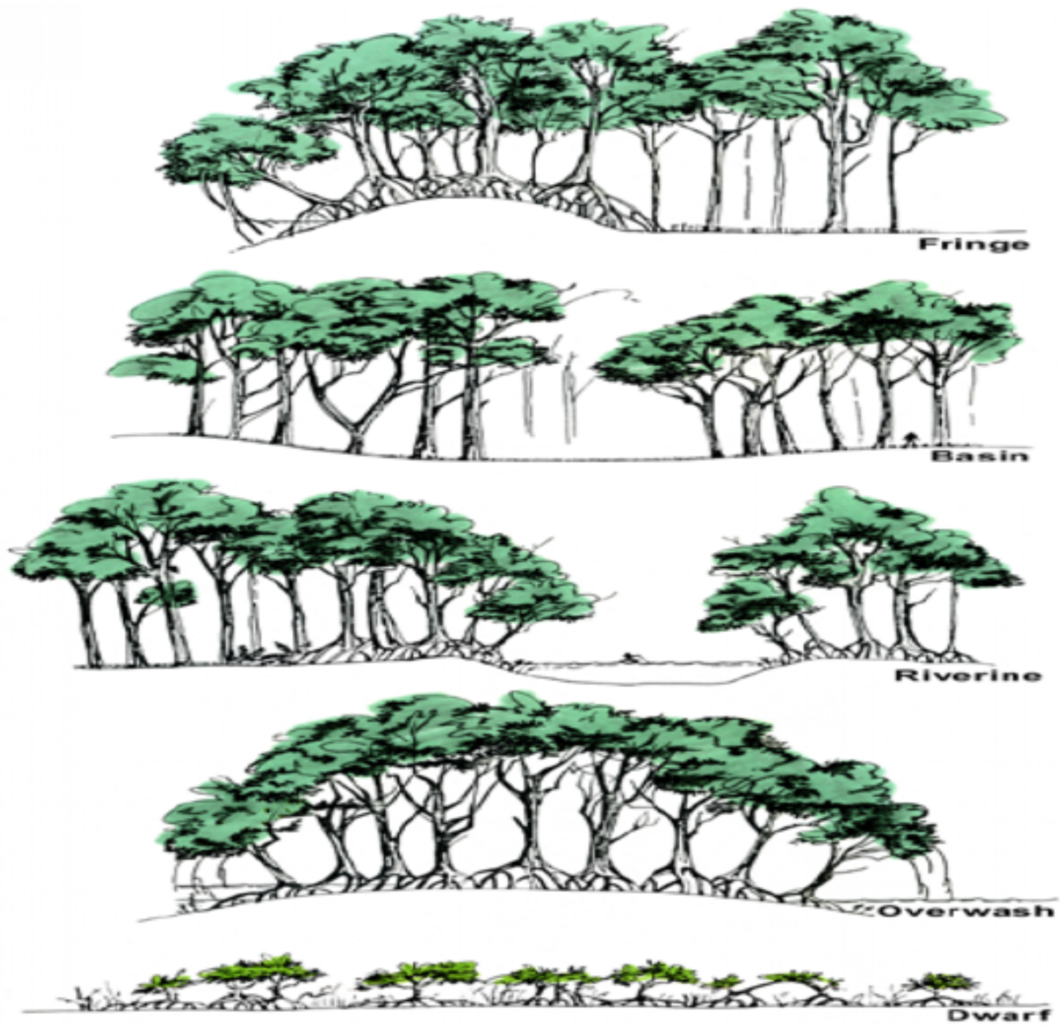

Figure 6: Types of Mangrove Forests (Lugo and Snedaker, 1974)

Elevation

Mangrove roots are known to hold soil together, thereby facilitating the accumulation of sediments that offer crucial elevation in the face of rising sea-levels (Krauss et al., 2014). Alteration of ground elevation, with respect to sea level and tidal range, is an essential function that impinges on how sustainable mangrove ecosystems become. Rising sea levels, sediment deposition and/or compaction, land subsidence, surface erosion and geologic activity all determine gains and losses in elevation. Mangrove ecosystems are noted for their comparatively lesser rates of decomposition (of leaves, roots, exudates etc.) that favours peat accretion and therefore increases elevation (McKee et al., 2007).

Elevation is additionally significant for its feedback into the dynamics of an ecosystem, as organic build-up and sedimentation are in turn affected by the nature of tidal flooding in relation to elevation. Kirwan and Megonigal (2014) for example, established this relationship in salt marshes, but according to Day *et al.*, (2018) mangrove ecosystems experience the same phenomenon, which results in areas with smaller tidal ranges being more susceptible to the effects of rising sea levels. The fact that saplings[21] are adapted to growth in non-flooded areas also acts as a positive feedback tool for their elevation promoting properties (Day et al., 2018). This is because as new mangroves grow and catalyse sediment accumulation, their offspring are also progressively provided with suitable substrate on newly reclaimed land for further colonisation, which expands populations for a boosted elevation-enhancing activity.

Decomposition

The breakdown of organic matter via microbial and invertebrate activity is a vital function for two major reasons. Apart from its implications for peat accretion and therefore elevation capital as mentioned earlier, decomposition also serves to support secondary production. In 2013, Maher and co-workers demonstrated how herbivores rely on a minor proportion of the live biomass involved in decomposition activity, and how other aspects of secondary production depend on the high organic transfers in mangrove ecosystems. The types of species involved in the process itself, the types of vegetation present and the structure of the ecosystem regulate decomposition

[21] Young trees with slender trunks

intensities. A slower decay rate is observed in impounded[22] mangrove environments; due to the aerobic constrains in same (McKee and Faulkner, 2000).

Decay activity determines the nature of biogeochemical cycling[23] because of its role in the release of nutrients. Nutrient accumulation within sediments accreted in mangrove wetlands goes a long way in facilitating their rates of removal from circulation within the habitat, thereby impacting processes such as eutrophication and chemical pollution (Mitsch and Gosselink, 2015). Nitrogen is especially important in this regard, as the fluctuating dissolved oxygen levels in aquatic mangrove environments create the conditions necessary for both nitrification and denitrification by microbiomes[24]. Carbon cycling is of similar import because of its implications on greenhouse gas stocks. Abiotic fluctuations (salinity, water, light intensity etc.) not only affect carbon sequestration through their roles in controlling primary production, but also impact decomposition patterns that determine effluxes of CO_2, CH_4 and NO_2 (Chen et al., 2016). By inference, healthier revegetated mangroves resolve as carbon sinks, whereas unhealthy degraded ecosystems with high dieback levels release more carbon.

Table 3: Ecological features of mangrove ecosystem integrity and associated indicator traits

Ecological Feature	Ecological Trait
Abiotic Factors	Temperature Soil properties Hydrology Nutrients Salinity
Ecosystem Organisation	Plant Community Structure Landscape Configuration Microbial Community Make-up
Ecosystem Function	Elevation Change Primary production Decomposition Secondary Production

[22] Diked for mosquito control through the intentional control of water levels.
[23] Cycling of chemical substances through the biotic and abiotic components of an ecosystem.
[24] Collection of microorganisms residing within a specific niche/environment

Ecological Functions

The extent to which mangroves re-acquire their natural ecological attributes following rehabilitation has not been conclusively established (Crona and Rönnbäck, 2005). There is some consensus on the progression of the replanted vegetation in terms of density, which is identical to what pertains in nature. After establishment, an accelerated growth and development phase ensues, ending in senescence with advancement of age (Clough et al., 1999; Jimenez et al., 1985; Ward et al., 2006)

Return of faunal diversity to the rehabilitated ecosystem is viewed as another indicator of ecological renewal, but has not been as extensively probed as the ecology of the mangrove trees themselves (Hogarth, 2015). Higher tree densities with flourishing faunal populations and habitat heterogeneity appreciation are, however, associated with maturity. Macintosh *et al*., (2002) and Walton *et al*., (2007) reported substantial crustacean and mollusc population increases with time within replanted mangrove ecosystems in Thailand and the Philippines, respectively. The progressive increase in productivity and structural diversity is also postulated to favour general improvements in the function of undisturbed, restored ecosystems as feeding, breeding, and nursery sites for fisheries (Sheridan and Hays, 2003; Bosire et al., 2005). Crona and Rönnbäck (2005) suggest that this situation becomes even more apparent and profound when compared with the status of similar populations in degraded mangrove ecosystems.

Successful return of ecosystem integrity and functioning following replanting is relative, with issues such as tree establishment, failed transformation into natural systems and continued anthropogenic interference being key considerations. Without tackling the degradative influences, the maintenance of optimum habitat conditions required for the new trees to thrive will be absent (Lewis III, 2005). Of particular importance is the need to reverse or halt all impediments to the natural regeneration process, in addition to planting the pioneer seedlings, to ensure establishment (Hong, 2004). In areas where environmental changes are extensive and irreversible (e.g., abandoned aquaculture sites with acid sulphate soils and ground subsidence problems (Wolanski et al., 2004)), replanting may not be advisable. Limited tidal inundation sites are also typically unattractive for replanting for propagule dispersal reasons, and must be stripped of their stressors before replanting can be considered (Lugo, 1992). Planting of mixed instead of monocultures of trees helps to eliminate ecological problems like pest infestations and predation (Bosire et al., 2005). Diversity in replanted vegetation also aids the ecosystem in supporting a wider array of aquatic and terrestrial flora and fauna (Das et al., 1997). Complete conservation of functionality, however, may be an unrealistic expectation in rehabilitated mangrove ecosystems. This is especially valid where key fauna has been lost, soil damage is extensive and human influences still linger (Macintosh et al., 2002; Kairo et al., 2001). However, valuable services are still reinstated following mangrove restoration attempts.

Anthropocentric Functions

All the biogeochemical and ecological functions that stand to be regained with mangrove rehabilitation are deemed important because they have anthropocentric implications. Coastal stabilization, storm protection, fisheries support etc. are all vital human wellbeing associated services. This is so because of the contributions they make to local economies, and this significance is retained even with replanted mangroves (Iftekhar and Takama, 2008).

Some research has been directed at quantifying the increase that these provisions experience following replanting, as a primary objective for projects of this nature. Binh et al., (1997) found that the value of returning benefits could be as much as five times higher than the cost of such projects. However, these figures, which hover around US$564 to US$2316 $ha^{-1}year^{-1}$, tend to be significantly lower than estimates provided for natural mangrove communities in similar locations. Sathirathai and Barbier (2001) for example, valued the direct and indirect services of Thai natural mangroves to be between US$27,267 and US$35,921 $ha^{-1}year^{-1}$. Clearly natural mangrove ecosystems provide services of higher value, but in their absence, rehabilitation of mangroves provides a definite desirable pathway for the return of these services.

2.3 PART THREE - THE MALARIA PROBLEM

2.3.1 INTRODUCTION

Historical evidence from most human civilizations demonstrates that malaria has been with humanity for centuries. Over half a million people worldwide die from malaria every year, an infectious tropical disease that is transmitted by female *Anopheles* mosquitoes. Although both preventable and treatable in most cases, the disease continues to wreak havoc especially in sub-Saharan Africa (The Global Fund, 2016). It is especially a grave public health concern because of its impacts on the poor, women and children, whose illness and subsequent mortality make tackling the disease a global emergency.

Transmission is often seasonal and limited to places where tropical temperatures and environmental conditions are conducive for the thriving of the vector organisms. Malaria peaks in the rainy seasons of Africa, Asia, and South America where the disease is endemic. While symptoms differ depending on the strain of the causative plasmodium parasite[25] involved, headaches, chills, body aches, drowsiness and sometimes delirium are indicative of malarial fever. A simple blood smear with microscope-assisted identification of the plasmodium parasite confirms infection, but in remote areas a Rapid Diagnostic Test (RDT) constitutes a reliable testing method (WHO, 2018b).

Having previously been handled with quinine drugs and their derivatives, current malaria therapeutic regimens consist of orally administered Artemisinin Combination Treatment (ACT) medication. Untreated malaria usually results in complications like kidney failure, anaemia, jaundice, seizures, coma, and death in extreme cases (WHO, 2012). Drug therapy is often successful, provided the right dosage is administered, instructions are followed and the side effects (which include nausea, dizziness, and headaches etc.) are well tolerated.

[25] Genus of unicellular protozoan organisms which partially develop in insect hosts and elicits malaria symptoms when transmitted to humans.

The parasites' main route to infection is via the bloodstream through to the liver where replication occurs, destroying red blood cells throughout the body. Causative parasites are of the plasmodium protozoan species transmitted though bites of the female *Anopheles* mosquito. Four of these have been so far identified and researched extensively. These are *Plasmodium falciparum* (which can be the deadliest) (Tabbabi, 2018), *Plasmodium ovale*, *Plasmodium malariae* and *Plasmodium vivax*. While the parasite may remain latent and take up to a year to elicit symptoms in the victim (e.g., *P. malariae*), the typical incubation period is thought to be 18 days. This could however be anywhere between 10 to 35 days for early primary attack. Long term effects are usually observed only in cases of cerebral malaria caused by *Plasmodium falciparum* (WHO, 2012), and they manifest in the form of neurological complications that are catalysed by a lack of timely and proper treatment. In pregnant women a weakened immune system can make the disease particularly devastating, leading to anaemia and placental parasitaemia, and having a bearing on neonatal and maternal survival (Asante and Asenso-Okyere, 2003)

Despite huge investments and progress in the control of the disease, malaria remains the leading cause of under-five child mortality in affected areas. It is a tremendous contributor to poverty and socio-economic inequity in Africa. It prevents children from attending school regularly (Wernsdofer and McGregor, 1998), and the working population from being at their most productive through a reduction in human capital accretion (WHO/UNICEF, 2003). The most overwhelming effect of malaria is the toll it takes on the household production of the mostly poor victims, who spend substantial portions of their earnings on seeking health care (Asante and Asenso-Okyere, 2003).

Every $1 investment in malaria control is estimated to translate into a $40 return in economic growth, with every 10% decrease in malaria incidence being associated with a 0.3% elevation of GDP (Gross Domestic Product) in affected regions (Gallup and Sachs, 2001). In effect, malaria hampers economic growth and undermines poverty reduction strategies. Even though progress has been made in acquiring the knowledge and tools required to combat malaria, the fight against the disease is still an on-going one. If the associated setbacks are to be overcome for countries facing malaria to prosper, a more holistic and less conventional approach which focus not only on control and treatment, but also on completely eradicating the disease, might need to be incorporated. This implies that the need to tackle the root causes of the spread of the disease, which are environmental in nature, has never been more germane. Tackling the causative foundations of malaria could be key to unleashing full potential for economic growth, as well as for unlocking human capital towards the assurance of a better quality of life in affected areas. In Ghana, focusing more attention on environmental dimensions of malaria risk could unlock more equitable health outcomes for communities experiencing reduced effectiveness of public health interventions.

2.3.2 MALARIA IN GHANA

2.3.2.1 Prevalence

The leading cause of morbidity and mortality in Ghana (Figure 7), malaria accounts for up to 40% of all outpatient cases in health facilities (Ameme et al., 2014). About a decade ago, up to 30% of deaths reported in children under five years of age, and 11% of maternal mortality in Ghana was attributable to malaria (MOH, 2009). The World Health Organisation presents slightly more conservative figures for these estimates, to account for the fact that a sizeable number of childhood deaths occur at home with no formal malaria diagnosis. They also compensate for the occasional misdiagnosis of other febrile diseases as malaria in Ghana's health centres (Aregawi et al., 2009).

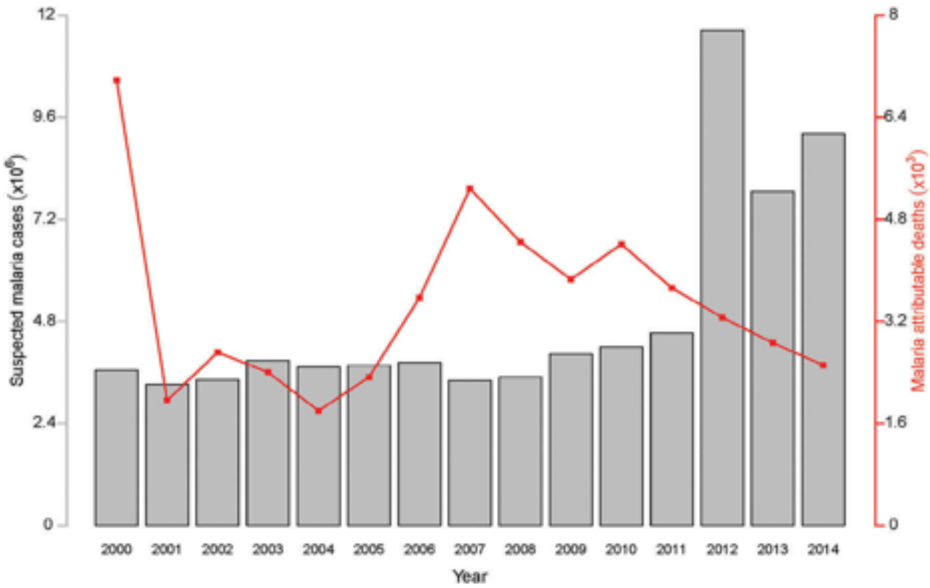

Figure 7: Suspected malaria cases and malaria attributable deaths from 2000 to 2014. (Awine et al., 2017).

It is worth noting that 6-59-month-old child mortality attributable to malaria reduced from an estimated 14.4% in 2002 to 0.6% in 2012 (GHS, 2013) . In formulating malaria policy, routine health data collection and surveys are conducted, which depict a high prevalence rate of the disease throughout the country (Ghana Statistical Service, 2011; 2014). Transmission is heterogeneous in nature, varying with the respective ecological zones in Figure 3. The single wet season that runs from June to October is the period within which the disease peaks in the northern savannah zone, whereas the forest and coastal ecological areas experience two peak seasons; first between March to July and then later from September to November (Owusu and Waylen, 2013).

2.3.2.2 Control and Management

Anopheles gambiae and *Anopheles funestas* are the principal mosquito vectors in Ghana, whereas the key parasite is *Plasmodium falciparum*, accounting for nearly 95% of cases. Although isolated cases of *Plasmodium malariae* and *Plasmodium ovale* have been identified (often manifesting as mixed infections alongside *Plasmodium falciparum*), *Plasmodium vivax* remains unreported altogether (WHO, 2015).

According to the WHO (2018a), for every 1000 Ghanaians at risk of malaria, at least 266 contracted the disease in 2015. Malaria control interventions in Ghana have been in existence for over 6 decades, with various therapeutic combinations having been tested as far back as the 1950s. Medications that have been used to varying extents include daraprim, chloroquine and amodiaquine-pyrimethamine among others (NMCP, 2013). With parasite resistance to chloroquine (first confirmed for *P. falciparum* by Afari et al., (1989), policy directives changed the first-line treatment for uncomplicated malaria to artesunate-amodiaquine in 2004. Subsequent revisions also incorporated artemether-lumefantrine and dihydroartemisinin-piperaquine combinations into the mix (Health, 2009). Various vector control strategies have also been executed alongside controlling the morbidity and mortality effects of the disease. Major cities have experienced limited roll outs of limited Indoor Residual Spraying (IRS) and Insecticide Treated bed Net (ITN) distribution initiatives since 1996 (GHS, 2013; NMCP, 2013).

Although medication coverage (ACTs) as well as vector control schemes (ITNs, IRSs) have been tremendously extended over the years (Figure 8), malaria morbidity in Ghana has comparatively remained elevated, sparking fears of elimination impossibility. By 2020, Ghana hoped to have reduced the burden imposed by the malaria pandemic by up to 75% (GHS, 2013), in anticipation of complete elimination of the disease by 2030 in line with Global Malaria Program (GMP) objectives (Awine et al., 2017). Considering the reality of widespread uncertainties relating to attainment of said targets (WHO, 2016), the persistent challenge lies in formulating new devices for revamping the existing intervention strategies.

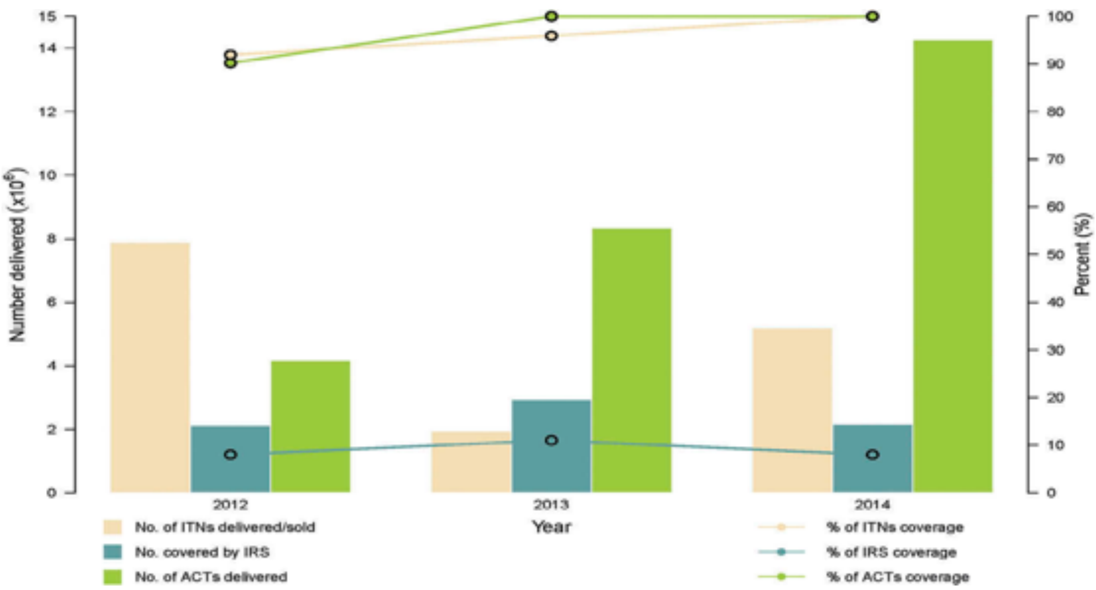

Figure 8 Malaria Interventions Delivery and Coverage from 2012 to 2014 (data source: (WHO, 2015).

2.3.3 ECONOMIC BURDEN OF MALARIA IN GHANA

While being pervasive throughout the country, malaria incidence is more commonly associated with the poor state of the environment as well as the deplorable socio-economic conditions of low-income communities in Ghana. This reinforces a vicious cycle of poverty, given the fact that these sections of the society are already plagued with resource scarcity (Shepard et al., 1991).

2.3.3.1 Direct Costs

The Government, individuals, whole households and sometimes healthcare providers share the malaria-associated costs in various forms, depending on the circumstances of malaria morbidity. Apart from the sickness, pain and death associated with the disease, other direct costs come in the form of having to take preventive and curative measures. Akazili (2002) for example, reported that in northern Ghana, 34% of household income goes into the costs of malaria treatment, whereas richer households elsewhere spent only 1% for the same purposes. The $2 per adult dose cost of the recommended artemisinin treatment regime for the disease constitutes a considerable proportion of incomes in poor households (Tabbabi, 2018). This income limitation often feeds into the widespread practice of self-medication, with patients typically seeking medical consultation only when they have been unsuccessful in dealing with their initial symptoms on their own (Asenso-Okyere and Dzator, 1997). The fear of contracting the disease motivates people to actively seek ways of averting infection, which invariably involves spending. Thankfully, a roll-out of a universal health insurance scheme in 2003 has minimised basic treatment costs for the disease, although effectiveness of the scheme is only moderate (Escribano-Ferrer et al., 2016).

Other government of Ghana's intervention strategies have usually included subsidies e.g., for ITNs, sponsorship of IRS exercises and tax exemptions for anti-malarial products (Asante and Asenso-Okyere, 2003). This constitutes a non-private medical cost borne by national health institutions. However, taking advantage of these mediation schemes would still sometimes involve some individual or household expenditure, often to buy drugs and to take preventive measures. Businesses are not left out in the monetary loss casualty list either.

As the prominent cause of work absenteeism, malaria presents a key obstacle in the sustainability, competitiveness, and profitability journey of most establishments. With a sick employee usually suffering more than two episodes of malaria each year, and including the time taken off work to attend to other sick relatives, companies suffer some of the heaviest losses. Well-resourced companies should consequently play significant roles in the fight against malaria, especially in the aspects where public agencies fall short, (e.g., technical expertise, funding, access to remote areas etc.). In Ghana, businesses that have deployed resources and infrastructure towards malaria control as part of corporate social responsibility have achieved interceptive results that would otherwise not have been possible. AngloGold Ashanti, a gold mining company in Ghana for example was able to achieve a staggering 74% reduction in malaria prevalence in Obuasi, even though they had targeted only 50%. Their private sector investment delivered benefits for the society as well as their business, reducing their monthly healthcare spending from $55,000 to $9800 and slashing worker absenteeism by 96% (Mouzin et al., 2011).

2.3.3.2 Indirect Costs

The debilitating effects of malaria (being the fever, body aches, nausea, vomiting, sweating etc.) make it impossible for sufferers to engage in any productive activity. Often a victim can remain bed-ridden and extremely weak, with dizzy spells making attentiveness impossible. In effect, working for an income becomes impossible for the duration of a typical bout of the disease.

Relatives or guardians of a sick person may have to cut down work hours or completely take time off work to cater for their sick household members, further reducing income acquisition potential for the period. The missed opportunity to obtain earnings amounts to an 'indirect cost' because like the spending that comes with seeking treatment, this phenomenon results in an eventual curtailment of potential household income. This indirect cost of illness is estimable via Harwood's (1994) 'Human Capital approach', which fits within the 'opportunity cost framework of market economics.

The reduced interest in utilising land that is mosquito-infested and therefore a prime location for malaria contraction, constitutes yet another indirect effect of the disease. This has bearings on the prospective tourism opportunities in the location for example, as well as land desirability for certain agricultural and industrial uses. The local economy therefore stands to suffer in the absence of these lost enterprises, as was the case in one Brazilian case study (Zhang et al., 2011). This is because the strategy of avoiding living and working within such locations presents an undesirable opportunity cost for land custodians.

Mortality associated with malaria robs communities of present and future human capital. Labour forfeitures amount to a loss in economic product, which according to Hodgson and Meiners (1992), is specified by the discounted potential earnings of an otherwise protracted life expectancy. Given the agriculture-based subsistence economies predominant in Ghana, and provided the assumption that land is readily available is valid, then this labour component stands to be a vital constituent of production, in line with suggestions made by Brandt (1980).

2.3.4 SOCIAL BURDEN OF MALARIA IN GHANA

The accurate description of what the term 'social burden' means within the context of malaria control is unclear. There is a consensus among public health practitioners that the social burden of the disease transcends its social costs, but according to Jones and Williams (2004) the definition of the concept itself remains vague.

While the quantified economic weight of malaria prevalence has been repeatedly reported within the international research fraternity, the same cannot be said for its social counterpart (Chima et al., 2002; Gallup and Sachs, 2001). Sachs and Malaney (2002) suggest that the costs that society incurs due to malaria has to do with behavioural changes that are often linked to broader economic matters. This implies therefore, that analysis of the social burden of malaria can only be conducted within the context of quantification of its associated economic fallouts, so that the social becomes a subclass of the economic. A slightly different viewpoint on the total validity of this approach comes to the fore when the assumptions made therein are considered.

In limiting the concept of 'social burden' to only what is dictated by the resolution of the economic dimensions of the incidence of malaria, the part played by other factors like culture, politics and beliefs not captured by traditional economic methods are likely to be ignored. These aspects have a significant bearing on how the disease is eventually distributed. Heggenhougen (2000) advocates why issues of power relationships, marginalization, racism, inequity etc. would normally influence the nature, enormity, and distribution of the burden of disease. Most control programs are increasingly acknowledging these determinants, but the positivist nature of biomedicine in practice however makes it difficult to make the case for this in tangible terms (Jones and Williams, 2004). Further, because scientific truths are expected to be necessarily observable, measurable, and quantifiable, the concept of social burden may vary from one society to the next. Disparities could be observed between two or more cultures, generations, individuals, or periods, so that generalisation becomes difficult. Nonetheless, understanding the concept of social burden (through an appraisal of perceptions) could be a useful route to formulating better policies for combative action within an anthropological framework (Keesing, 1981). In the following sections some of these perspectives are explored in relation to malaria in Ghana.

2.3.4.1 Poverty and Social Inequities

The poverty and therefore deprivation that is widespread in Ghana dictates a certain lack of educational, resource and health management empowerment that is necessary to deal with bouts of malaria. The poor are often isolated to marginal lands and remote locations that, in addition to being bereft of the environmental integrity necessary to control the risk of malaria and other infectious diseases, are plagued with limited access to health and financial services as well. Women bear the bigger brunt of this social exclusion, being more disadvantaged in almost all well-being indicators (Lampietti and Stalker, 2000).

In a study conducted by Krefis et al., (2010) in Ghana, principal component analysis (PCA) was used to reduce the information on seven indicators of the housing situation of children reporting with malaria at health facilities, into a socioeconomic score. When these scores were analysed along with other co-factors that influence malaria risk, it became evident that the fraction of infected children declined with increasing socioeconomic status. Since relative homogeneity of economic statuses prevails in rural Ghana, the significance of socioeconomic circumstances and how it affects malaria prevalence becomes apparent.

Chronic poverty within deprived sections of society also tends to limit the quality of food that a household can afford. Income levels would determine the quantity of food available as well as the nature of the ingredients of family meals, thereby having an influence on overall nutrition. Being malnourished, which surpasses mere protein-energy malnutrition to include deficiencies in micronutrients too, affects the impact a typical malaria episode would have on a household. Iron, Zinc, Iodine and Vitamin A are nutrients that are relevant to a person's ability to recover from disease due to their involvement in the processes leading to a robust immune system. Insufficiencies in these nutrients as components of and in addition to general malnutrition increase malaria morbidity and mortality (Caulfield et al., 2004). A study conducted by Mockenhaupt et al., (2004) in northern Ghana demonstrates the role played by malnutrition in the way malaria manifests in deprived areas of the country. Their results suggest that while children hospitalized with malaria present with severe anemic conditions, this was not indicative of mortality susceptibility, stipulating that malnutrition was the more likely predictor of mortality. This observation was further substantiated through the work of Ehrhardt *et al*. (2006), which produced equivalent results. This comes through as reasonable, as malnutrition hampers the body's ability to heal itself, to recover from and to actively fight the devastation brought on by a parasitic infection.

2.3.4.2 Social Marginalisation

Another striking characteristic of destitution is the reinforcement effect on other aspects of social exclusion. Issues such as inequities based on gender, race, ethnicity, and geographic location stand to be aggravated by low-income levels in sections of society, manifesting in comparatively inferior levels of development in those areas (WHO, 2006c). In less developed communities it is common to observe for example, sub-standard and inadequate housing that are hurriedly constructed without protective add-ons like screened windows. People in such areas would naturally make use of what affordable materials are at hand, rarely budgeting for the vital additions which, while being perceived as frivolous in those parts, would offer protection from vector contact. Overcrowding in same kind of environments also gives rise to higher concentrations of body heat, carbon dioxide and other chemical levels within such dwellings; conditions that have been proven to attract mosquitoes (Alton and Rattanavong, 2004; Lindsay et al., 2003).

One interesting link between the kinds of occupations that exist in rural areas in Africa and malaria risk was revealed by the work of Filmer, (2001). This study concluded that the necessarily manifold sources of livelihoods in marginal communities means that people are often compelled to collect goods and services from their natural environments. Specifically, increased forest endeavours for occupational purposes exposes people to an elevated risk of malaria, which is then transferred to other members of households. Deductively, this accelerated risk also exists for people who migrate into settlements that are closer to forests in search of better livelihood opportunities that come with forest resource dependence. This increases the possibility of contact with vector organisms, which is postulated to lead to even greater incidence of the disease (Gottwalt, 2013). Because vector control is one of the most crucial management strategies in malaria control, the dynamics of increased vector exposure becomes relevant to disease susceptibility.

Jones and Williams (2004) additionally comment that poor health provider attitudes and unwillingness to serve in remote deprived areas, which results in an inadequately resourced healthcare delivery, also contributes to the deficits faced in marginalized communities when it comes to malaria control. As a result, confidence in the healthcare system is significantly reduced, so that the likelihood of seeking treatment through that channel could further decline.

2.3.4.3 Socio-Cultural Practices

The decision to seek medical attention for malaria sometimes depends on the cultural practices of sections of the Ghanaian society. Certain sociocultural variables that draw from literacy levels, experiences and understandings surrounding malaria illness can sometimes delay the treatment-seeking action, leading to unfavorable effects on morbidity and mortality. According to Ahorlu (2005), some rural folks in Ghana would opt for traditional herbal products prepared at home, by boiling known plant materials, instead of attending hospitals. This poverty-related preference, which potentially undermines malaria control strategies, stems from the costly nature of orthodox medicine, and the limitations imposed by a further lack of access to health facilities. While there is strong indigenous belief in the efficacy of local herbal treatments, absence of concrete pharmacological knowledge about these preparations raises concerns regarding how the disease could be eliminated under such unapproved, unverified regimes.

2.3.4.4 Gender-Related Factors

Inequalities in gender issues also contributes to imbalances in the social burden of malaria in Ghana. Traditional gender roles that are reinforced by patriarchal systems in rural societies all but ensure that women remain at a disadvantage when it comes to predisposition to malaria. Resource allocation, decision making and financial power in some households are often heavily skewed in favour of men, so that women are sometimes disadvantaged when it comes to the empowerment and choice to seek medical attention (WHO, 2006a). Moreover, the entrenched gender roles in indigenous Ghanaian settings dictate that women must take responsibility for household chores, which almost always involve staying outdoors longer than their male counterparts late at night or at dawn. Since this situation exposes them to greater contact with mosquitoes, women tend to suffer greater burden from the disease owing to cultural practices (WHO, 2006b).

Ricci (2012) points out how honors enjoyed by men as ‘heads of households’ means that they get to enjoy certain malaria-protective privileges that women and children do not, such as better nutrition, access to limited ITNs etc. These considerations must inform the design of malaria control strategies, because eliminating inequities of this nature influences risks and associated consequences that women and children face in respect of the disease.

2.4 PART FOUR - MANGROVE DEFORESTATION AND ANOPHELINE DISEASE

2.4.1 THE CONCEPT

Although the definite origin of malaria is quite inadequately documented, its historic expansion has been shown to have coincided with the advent of agriculture in Africa and the Middle East (Laderman, 2002). This suggests that any activity that alters natural environments for agricultural purposes could be a potential aggravator of the disease; and, conversely, that an attempt to restore close-to-natural ecosystem integrity could constitute an effective malaria control tool within a location.

Anthropogenic involvements in forest ecosystems influence the spreading and incidence of vector-borne diseases within surrounding populations (Gottwalt, 2013). According to Walsh *et al.,* (1993) disease patterns, vector ecology and vector behaviour in West and Central Africa are related to land transformations and deforestation. They comment that the very anthropophilic[26] *A. gambiae* complex mosquito vectors dominant in the region have become progressively adapted to larval habitats that are made increasingly available through deforestation activities. Rajavel and Natarajan (2008) make specific reference to anthropogenic environmental changes like logging and land reclamation for agriculture as impacting negatively on mangal ecosystems and influencing inherent specie configuration.

The epidemiology of malaria is altered when changes in the abundance of the relevant *Anopheles* mosquito vectors occur. Because these vectors breed in standing water, deforestation and any land use alterations that create new spaces for water accumulation tend to exacerbate their numbers. The ecological demarcations in Ghana each display unique characteristics in relation to malaria parasite form and vector prevalence. Dissimilarities in temperature, rainfall, humidity, and ecology account for these differences in the principal malaria parasite vectors, *Anopheles gambiae* complex and *Anopheles funestas* (MOH, 1991). The implication is that any environmental variability, natural or otherwise, would have connotations on vector distribution and behaviour. *Anopheles melas*, a member of the *A. Gambiae* complex, is the most

[26] Greater attraction for human rather than animal victims and dwellings

abundant variant in coastal lagoonal areas and mangrove swamps in the Lower Volta region, Accra plains and the Lower Central region.

2.4.2 ECOSYSTEM RELATED CONSIDERATIONS

2.4.2.1 Temperature

Many malaria vectors breed in open sunlit pools, and forest clearance makes more of such habitats available for the mosquitoes (Walsh et al., 1993). Work done by Wolfarth et al., (2013) revealed how a direct statistical significance exists between malaria records and increasing temperatures in the Amazon. The writers indicate that land use changes that allow more sunlight penetration within a previously forested location could aggravate vector breeding. This theory is of particular significance in mangrove ecosystems because the nature of swamps would ordinarily promote mosquito breeding, but for the possible role of mangal woodland in regulating sunlight intensity. Clearing of mangroves in certain countries like Indonesia increased the incidence of certain species of Anopheles mosquito, because of the increase in the total area exposed to sunlight (Marwato and Arbani, 1991; Roundy, 1980). Another study conducted in Malaysia revealed that as shade-providing mangroves were cut in the 1920s for charcoal manufacture, suitable breeding grounds for the endemic malaria vector increased, along with malaria incidence (Ooi, 1959).

Higher temperatures particularly increase the likelihood of transmission because while the intrinsic incubation period for hatching is reduced, rates of biting, egg laying, and other vector behaviours are also likely to increase (Reiter, 2008). A series of entomological surveys carried out by Faye *et al* (1994) in Senegal compared malaria transmission intensities in villages close to and far away from a mangrove in the south of the country where *A. gambiae* complex was the principal vector. Results indicated that transmission intensity increased with increased distance away from the mangrove sites, relative to larval breeding sites of the mosquitoes.

2.4.2.2 Land Use Change

When alterations occur in the way natural forested land has been used, ecosystem boundaries are re-shaped, and the forest-human frontier is also moved closer to settlements. This increases the possibility of contact with vector organisms at the forest edge, which is postulated to lead to greater incidence of malaria (Gottwalt, 2013). Deforestation of the nature that occurs in mangrove ecosystems has a direct and measurable health impact on infectious disease emergence and acts as an important diagnostic measure of health in nearby human populations.

The other aspect of malaria control that could be influenced by land use changes in mangrove ecosystems is the phenomenon of insecticide resistance, with agricultural insecticide use and emergence of insecticide resistance in mosquitoes being linked in some studies. Diabate et al., (2002) for example, found that in neighbouring Burkina Faso, pyrethroid insecticide resistance was prevalent in mosquitoes of *Anopheles gambiae* complex in areas where agriculture had taken over natural ecosystems. In a more recent review conducted by Ranson and Lissenden (2016), it was clear that this trend is widespread throughout Africa, with dire implications for ITN and IRS strategies which use pyrethroid-based insecticides. Progress made in making ITNs and IRS programmes more widespread and accessible in even the remotest parts of countries like Ghana could be severely undermined if the active ingredients of these inputs become incompetent. Considering these findings, halting, and reversing land use alterations could be conceptualised as potentially beneficial to malaria control strategies. This is especially valid in locations close to swamps where the hydrology could promote vector breeding under degraded conditions.

2.4.2.3 Vector Behaviour

Adult mosquito emergence from the pupal stage of their life cycle is dependent of larval nutrition, with larger, more numerous populations of mosquitoes being connected to organic-matter-rich breeding environments (Grimstad and Walker, 1991; Sattler et al., 2005). Mangrove ecosystems, as mentioned in Part 1, promote nutrient cycling, and increase in organic matter content in mangal habitats. The expectation thereof is that healthy mangrove ecosystems would produce better-nourished, larger mosquitoes when they do breed within the ecosystem. In the *A. gambiae* complex, this would mean larger, more parasite competent females who would be expected to influence malaria transmission (Okech et al., 2007), as they seek hosts for the blood meal required for egg maturation. However, other studies like Takken et al.,(1998) also submit that because larger, more nourished adult *Anopheles gambiae* mosquitoes emerging from nutrient rich environments have fewer nutrient deficits, they tend to be initially less aggressive in seeking hosts for nutrient-rich-blood meals. In other words, smaller *Anopheles* mosquitoes, as would be observed in the nutrient-strained environments that characterise degraded wetland ecosystems, tend to seek hosts sooner and more aggressively than their better-formed, larger counterparts.

Furthermore, other research has also uncovered results to the effect that plasmodium-infected larger *Anopheles gambiae* mosquitoes die sooner than their smaller counterparts, making them less likely to transmit malaria within their lifespan. This has been explained to be due to the pathogenicity of the plasmodium parasite on the vector mosquitoes themselves. Lyimo and Koella (1992) for example, suggest that survival is low in infected larger mosquitoes because they ingest a greater number of plasmodium gametocytes[27] in their larger blood meals. Thus, even where a larger, better-formed mosquito ingests a blood meal infected with the plasmodium parasite, the probability of it transmitting its parasites to humans to cause disease is markedly reduced because the mosquito itself is likely to succumb to the infection first.

All these dynamics in vector behaviour, which are determined by their habitats, have potential implications for both malaria control and mangrove ecosystem management.

2.4.2.4 Biological Vector Population Control

Vector-focused control of malaria holds promise for eradication due to the inextricable nature of the connection between transmission and the life cycle of the vector mosquitoes. Biological control at the various vector life-cycle stages is of appeal because it circumvents the environmental considerations and insecticide resistance development issues that often characterise chemical vector control strategies

[27] The blood-stage parasites ingested through a blood meal complete their lifecycle in the insect stomach. This results in the formation of many sporozoites within a cyst-like structure (oocyst). The sporozoites are then ejected into the salivary glands of the insects, from where they re-infect humans in the next blood meal.

(Kamareddine, 2012). Moreover, it has been shown that in areas where *Anopheles* are exophilic[28], so that effects of residual spraying and impregnated nets are undermined, biological control mechanisms could be exceptionally useful (Shililu et al., 2004).

After eggs hatch in water, they transition through four larval stages through to a pupal stage and then to adult mosquitoes. Although adults feed on sugary substances like nectar, females require at least one blood meal to nourish their eggs after mating, through which process parasite transmission occurs (Ramirez et al., 2009). Factors relating to ecosystem functioning, such as dissolved salts, organic and inorganic matter content, level of eutrophication, turbidity, mud content, vegetation cover, pH, dissolved oxygen, and light intensity have all been shown to have an impact on both adult and offspring survival rates (Gimnig et al., 2001; Grillet, 2000). These factors are incidentally also influenced by ecosystem integrity. While some studies in Africa failed to uncover any concrete relationship between *Anopheles gambiae* distribution and the afore mentioned environmental variables (Minakawa et al., 1999), some more recent findings have revealed otherwise. These include research carried out in Eritrea and Kenya by Shililu *et al.*, (2003a) and Munga et al., (2005) respectively, which positively associated Anopheles species with widely sunlit shallow waters. These conditions are more likely in urban or peri-urban locations than in undisturbed mangrove ecosystems where an extensive vegetation cover, reduced evaporation and frequent inundation are inclined to inhibit such conditions. Little information however is available on whether this is true, and on how this stands to affect *Anopheles* distribution within wider ecosystems.

There is further evidence suggesting that in addition to location and the physico-chemical conditions of the aquatic environment, oviposition[29] preferences of mosquitoes are based also on the presence of potential predators as well as competitors (Piyaratne et al., 2005; Kramer and Garcia, 1989). Gravid[30] females use chemical and biological signals to shun environments that have abundant populations of other insect larvae (for example of the mayfly *Heptageniidae spp*.) which are likely to compete with

[28] Rests outdoors, and therefore engages in biting before victims retire to bed.
[29] Process of egg-laying
[30] Egg-carrying

their young for food sources (Blaustein and Kotler, 1993). Any wetland ecosystem that is functioning optimally and therefore supporting a complex array of water bugs is consequently expected to be avoided by breeding females in line with results from Muturi *et al*., (2008).

Bacteria, entomopathogenic[31] fungi, viruses, microsporidian[32] parasites, nematodes and larvivorous[33] fish have all been extensively studied and severally applied in pilot studies on mosquito control worldwide (Kamareddine, 2012). Larvivorous activities of diverse fauna, whose survival fortunes hinge on the integrity of wetland ecosystems, are also of relevance in this specific discussion. Various species of birds, fish, copepods, water bugs and amphibians that feed on adult mosquitoes and their juvenile stages, are likely to emerge following biodiversity-enhancing restoration attempts in mangrove ecosystems. In fact, the predatory activities of some of the applicable species are believed to be vital for maintenance of trophic equilibrium in aquatic ecosystems (Sih et al., 1985). Moreover, a healthy emergent cover of vegetation, which translates into a more supportive environment for a variety of potential larval predators, also tends to obstruct oviposition in mosquitoes. Vegetation limits the amount of sunlight hitting the water surface, so that temperatures are kept lower than optimum for the microbial proliferation rates required to offer nourishment to larvae. If the larvae are poorly nourished, their development is delayed so that they are at a bigger risk of predation (Rao, 1984).

2.5 CONCLUDING REMARKS

This review first outlines the status of mangrove forests within Ghana's wetlands. The general finding is that widespread harvesting of mangrove stands for livelihoods support has affected the integrity of mangrove ecosystems nationwide, with the Volta estuary suffering some of the most extensive degradation. Evidence from regions of Ghana that harbor mangrove ecosystems suggests that these very vital assemblages face threats from anthropological interference and environmental change. Overexploitation has

[31] Virulent against insect forms
[32] Spore-forming unicellular parasites
[33] Feeding on insect larvae

been exacerbated by the community land tenure systems in place in most of the mangrove locations in the country. Given the vast array of benefits that these vulnerable ecosystems provide for proximate communities and their ecological significance in general, it appears imperative to explore ways of preserving these ecosystems.

Recent restoration attempts, centered on replanting of the most resilient tree species, have been carried out across the country. These projects, which have seen varied levels of success, have been done as parts of general wetland conservation projects or as stand-alone ventures, sometimes with sustainable harvesting regimes implemented. Unfortunately, not much follow-up work has been done regarding the overall impact of such undertakings, both in terms of implications for rural livelihoods strategies and wellbeing, as well as the ecological benefits. This literature review has revealed the fact that replanting of mangroves can constitute a major step in the return of the ecosystem to proper functioning, with the promise of return of vital ecosystem services.

In Chapter 3, a more targeted systematic review is conducted to reveal current knowledge about the contributions of mangroves to human health. It remains to be fully confirmed if Ghana's mangroves and related restorative endeavors have delivered ecological and health-related improvements. The key informant interview assessment carried out in Chapter 4 of this study appraises mangrove use dynamics and post-revegetation ecosystem service changes in the study locations. This study further contributes to the limited information available on mangrove role in infectious disease risk (specifically relating to malaria) through causal inference analysis in Chapter 5. The findings on how mangrove conditions influence malaria incidence are then applied to explore policy enhancement opportunities for improved ecosystem and malaria and health management in Chapter 6. As malaria persist as a monumental health concern in Ghana, malaria eradication remains top of the public health agenda. The exploration of such malaria-relevant aspects of the on-going research agenda on mangrove ecosystems and human well-being could offer some useful additions to optimization of malaria control options.

CHAPTER 3: INVESTIGATING MANGROVE-HUMAN HEALTH RELATIONSHIPS: A SYSTEMATIC REVIEW OF CURRENT EVIDENCE

3.1 INTRODUCTION

The World Health Organisation (WHO) takes a broad stance on what health entails, defining it as “a complete state of physical, mental and social wellbeing, and not merely the absence of disease of infirmity” (2020). Health is accordingly not guaranteed by a mere absence of disease, without the full complement of biological, psychological, and social factors. The Millennium Ecosystem Assessment (MEA) (MA, 2005) identifies major ecosystem services linked to attainment of health-promoting conditions as: climate regulation, water purification, food, wood and fibre, flood regulation, freshwater provision, fuel supply, and disease regulation. Lesser-impacting educational, recreational, spiritual, and aesthetic services are also cited. Holistic health can thus be derived from the direct or accrued impacts of services supplied by key ecosystems, including mangroves.

The MEA catalysed growth in research and a greater appreciation of the need for protection, restoration, and conservation of ecosystems. As evidence of health-related benefits of well-functioning ecosystems become better established, the academic space is simultaneously confronted with indications of rapid and widespread decline in the supply of ecosystem services. Anthropogenic interferences are compromising the abilities of many of the world’s most vital ecosystems to provide life-supporting services (Costanza and Daly, 1992; Dirzo et al., 2014; Sala and Knowlton, 2006; Ceballos et al., 2015). With issues like climate change and rising populations further increasing the pressures on these ecosystems, there have a been growing calls for changes in policy direction, particularly, those that incorporate knowledge of the nature-health relationship (Myers et al., 2013; Bauch et al., 2015). A clear understanding of this relationship is however selectively scarce in the literature, especially for non-terrestrial ecosystems. (Barbier, 2012).

A cursory look at ecosystem assessments shows skewed attention on terrestrial ecosystems, leaving the mapping of 'marine and coastal ecosystem services' (MCES) at a distinct disadvantage (Liquete et al., 2013). This gap has been attributed partly to the limited availability of tools for pinpointing high-resolution and overt information relating to MCES (Maes et al., 2012; Somerfield et al., 2008). A further inadequacy is the lack of a customised valuation system for MCES, many of which have relied on indicators and proxy ecosystem service data fine-tuned for terrestrial ecosystems (Egoh et al., 2012; Layke et al., 2012). The lack of robust biophysical measurement and social assessment regimes in the face of exploitation for rapid human advancement, has often favoured the demise of some critically threatened MCES ecosystems. This is especially true for mangroves, which have not only been designated as 'wastelands' historically, but also subjected to weak valuation mechanisms that have progressively favoured their loss (Aburto-Oropeza et al., 2008).

Mangrove ecosystems, found at the interface between terrestrial and marine ecosystems, and dominated by unique plant communities, are adapted to a variety of alterable conditions of substrates, oxygen levels, salinity, and temperatures. Studies such as Duke et al., (2014) outline how loss of a wide range of natural mangrove products and ecological services can limit human health in particular (Figure 9), and wellbeing in general.

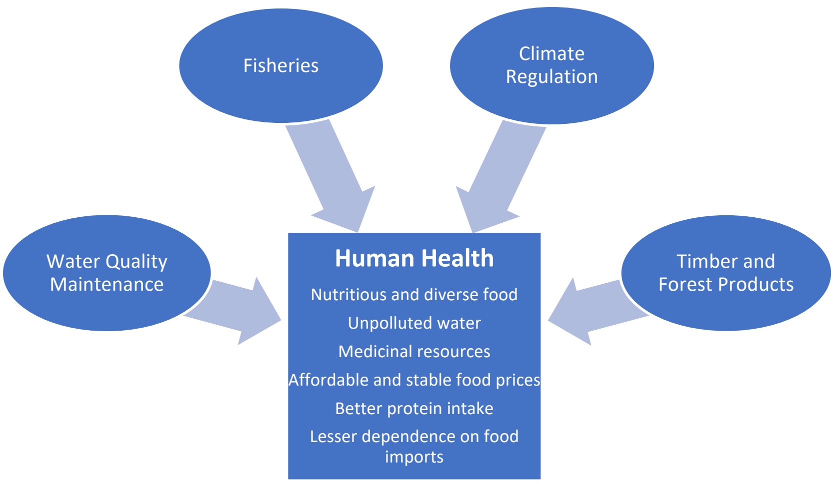

Figure 9: Mangrove ecosystem goods and services and their human health impacts that are lost with ecosystem degradation (adapted from Duke et al., 2014)

Alongside natural disruptive phenomena, anthropogenic interferences unfortunately continue to subject these specialised ecosystems to undue stress, leading to continued losses in cover (Rönnbäck, 1999; Polidoro et al., 2010). Health-related mangrove literature however remains sparse and fragmented, in contrast to the situation regarding other terrestrial habitats and corals. The few mangrove reviews found have concentrated on ecological characteristics, economic value, impacts of environmental change on ecosystem resilience etc (Table 4), with none focusing on human health links.

Table 4: Sample Collection of Mangrove Ecosystem Reviews

Ecological chemistry	(Che, 1999) (MacFarlane et al., 2003) (Defew et al., 2005; Lewis et al., 2011)
Historical characteristics	(Walsh, 1974) (Hogarth, 2007)
Habitat function	(Nagelkerken et al., 2008)
Macrobenthos	(Lee, 2008)
Economic value	(Rönnbäck, 1999)
Medicinal uses	(Bandaranayake, 2002; Velmani et al., 2016; Thatoi et al., 2016)
Nutrition	(Reef et al., 2010)
Effects of oils and dispersants	(Thorhaug, 1989) (Burns et al., 1993) (Proffitt, 1997) (Hoff, 2002)
Climate change	(McKee, 2004) (Gilman et al., 2008)

In addressing the highlighted gap in knowledge, the objective of this systematic review is to outline current and potential relationships between mangrove ecosystem services and human health, by answering these research questions:

- RQi. What are the perspectives in the literature about the medicinal properties of derivatives of mangroves and mangrove associates?
- RQii. What is the available evidence about the attenuating effects of mangrove ecosystems against pollutants that pose human health threats?
- RQiii. In what ways do mangroves directly (or indirectly) support provision of goods that contribute to healthy human nutrition?
- RQiv. What is the nature of the impact exerted by mangrove ecosystems on the abundance and distribution of causal agents and vectors of human disease?

In the absence of a definitive causality framework, recently observed and potential linkages between human health components and services from mangrove ecosystems are reviewed. The WHO definition of health is used to appraise the relevance of ecosystem services provided by mangroves to humans, as submitted by Duke et al. (2014). It is acknowledged, in adopting this approach, that no absolute certainty can be alluded to in the linkages that are drawn between human health and mangrove ecosystem services. This review nonetheless provides some context regarding what is noteworthy in decision and policy making around the mangrove-human health nexus, and towards concurrent delivery of health and environmental sustainability outcomes.

3.2 METHODOLOGY

3.2.1 Literature Search and Selection Criteria

This review used the 'Guidelines for Systematic Review in Conservation and Environmental Management' (Pullin and Stewart, 2006), as well as the PRISMA[34] methodological guidelines for transparent reporting of systematic reviews (Page et al., 2021). It consists of a systematic and selective literature assessment on the results of a broad search of relevant content on health-related mangrove ecosystem services. Using the ISI Web of Science database, sets of comprehensive bibliographical searches were conducted using two sets of keywords: 'mangrove ecosystems' AND 'human health', or 'mangroves' AND 'human health', between the year 2000 to 31st July 2020. The year 2000 was chosen to include only recent and presumably more reliable knowledge around the search parameters, and to minimise inherent assumptions and uncertainty about mangrove ecosystem goods and services. This resulted in 512 peer-reviewed publications on human health issues related to mangrove ecosystems. After elimination of duplicates, the resultant collection of 324 was subjected to the filtration steps of abstracts, full texts, and bibliographical lists examination using the inclusion and exclusion criteria outlined in section 3.2.2. Retrievals made from bibliographical cues were retained irrespective of publication year, provided full-text examination deemed them relevant to the review objectives. This combination of steps in Figure 10 generated a final list of 96 papers subjected to further examination and qualitative analyses.

[34] Preferred Reporting Items for Systematic Reviews and Meta-Analyses

3.2.2 Exclusion Criteria

The keyword searches returned a first set of literature that was filtered to exclude papers that focused solely on ecosystem-related 'ecological risk assessments', and therefore had no direct relationship with 'human health.' Only English language publications reporting a primary assessment of health-related mangrove ecosystem services were included in this review. Publications that included mangroves as part of a more general assessment of 'nature', or services of various ecosystems and human wellbeing, were deemed to be beyond the purview of this review. Such papers were excluded because apart from the time constraints that would be posed in doing so, there was no justifiable means of mapping mangrove ecosystems to specific health outcomes. Also excluded were secondary and comparative assessments of previously established health-promoting links or properties. Publications included in previous mangrove ecosystem service reviews were retained if they had assessed health-related effects. Potential impacts are inferred for studies that assess health links at a purely experimental level, even if there is no progression to results verification in living systems or communities. The PRISMA flow diagram is presented in Figure 10.

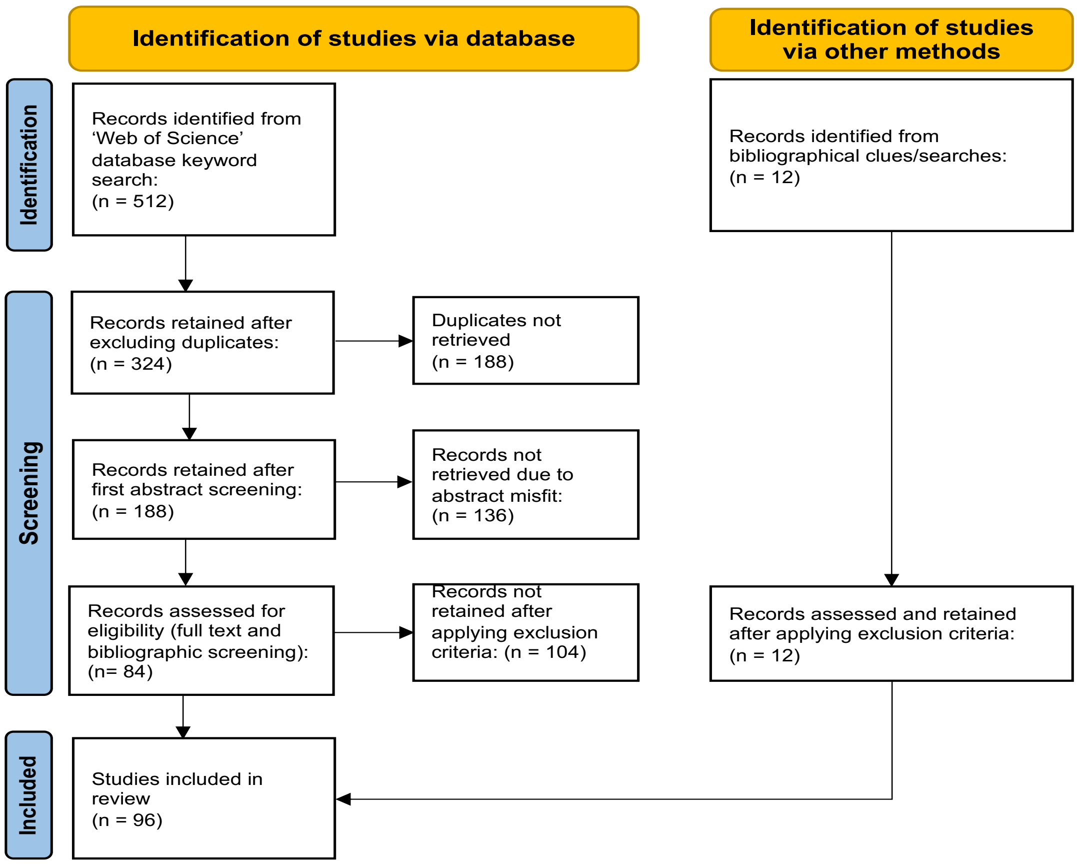

Figure 10: PRISMA methodology flow diagram for collation of studies included in this review.

3.2.3 Discussion Framework and Presentation of Findings

Graphical representations of studies on relevant mangrove ecosystem services and their associated health impacts (observed, perceived or potential) were developed, highlighting representative papers that signalled positive, negative, or no conceivable links to human health. Finally, the unique properties and functions of mangrove ecosystems that facilitate health-related services are presented and discussed alongside the review findings.

Using the WHO definition of 'health' and the MEA framework, food provisioning, regulation of water and sediment chemistry, provision of medicinal goods and disease regulation were identified from the retrieved records as the key health-related services supplied by mangrove ecosystems (Table 5). The presentation and discussion of results is conducted under these categories, with commentary on some of the key findings and their ecological underpinnings.

Table 5: Key health-related mangrove ecosystem services identified in the literature using MEA framework as a guide.

MEA Category	Mangrove Ecological Function	Mangrove Ecosystem Service/Disservice
Provisioning Services	Nutrient and biomass production and cycling for aquaculture, livestock, crop, and fisheries support	Influence on output of human food supply activities for nutritional support at subsistence and commercial scales (17 records)
	Phytochemical production by mangrove plant tissue and associates (e.g., endophytic fungi, actinobacteria etc)	Chemical isolates for medicinal and industrial application in human disease pathogen control and food preservation; bioactive compounds for alleviating human ailments (41 records)
Regulating Services	Bioremediation of pollutant constituents (organic and mineral) of waste discharges, oxygenation of dead zones	Attenuated impacts of heavy metal and hydrocarbon contamination of mangrove soil, food, and water sources (27 records)
	Regulation of abundance, spread and behaviour of pathogens and vectors of human disease through modification of biotic and abiotic habitat characteristics	Influence on the incidence and distribution of human pathogen-causing and vector mediated diseases (11 records)

3.3 RESULTS AND DISCUSSION

3.3.1 MEDICINAL VALUE OF MANGROVES

3.3.1.1 Background

Dependence on 'western medicine' has arguably become more widespread around the world, translating into a progressive decline in the reliance on indigenous knowledge on natural remedies which, for the most marginalised societies, tends to be otherwise invaluable. This shift could be precarious in the developing world, where risks of exposure to diseases, vectors, and nuisance insects persist due to limited implementation of public health models and low socio-economic statuses together. Given that a vast array of mangrove and mangal associates have long formed an integral part of folkloric disease management (Bandaranayake, 1998), their indispensable value in bridging this shortfall in the health delivery conversation is tangible.

Accounts of indigenous applications of mangrove extracts for astringent, antipyretic, anti-haemorrhagic, analgesic, anti-inflammatory and anti-ulcer purposes are plentiful (Bandaranayake, 2002). Numerous species of mangrove have also found traditional uses as sources of medicinal, pesticide and insecticide preparations, due to their richness in bioactive secondary metabolites (Patra and Thatoi, 2011). However, some of these phytochemicals naturally occur in mangroves plants in their precursor form, selectively undergoing activation under pathogenic attack or tissue impairment (Ncube et al., 2008). To understand the specific medicinal potential of mangrove ecosystem resources, there have been numerous characterizations of chemical derivatives of leaf, stem, bark, root, and sediment samples that have revealed extensive medicinal usefulness. Some reviews of these accounts exist in literature (Kathiresan et al., 2006; Bose and Bose, 2008; Wang et al., 2009).

3.3.1.2 Main Findings

In the current review, types of mangrove resources from which the compounds were extracted fall into three major categories: plant and plant associates, actinobacteria and endophytic fungi. These plants and associates produce metabolites that help mangrove plants deal with pathogenic invasions (Nurunnabi et al., 2018; Ling et al., 2016), implying potential antimicrobial applications. Flavonoids, phenols, terpenes, and aliphatic alcohols are a few of the types of bioactive compounds that have been widely identified as being responsible for the medicinal properties of mangrove resources. The species targeted for phytochemical assessments are those that have long-standing reputations within indigenous mangrove dwellers as being medicinally valuable.

Assays of bioactive mangrove-derived compounds captured in this review displayed antagonistic activity towards cancer cells, inflammation, fevers, pathogenic and food spoilage organisms, and diabetes mediating enzymes (Figure 11). Each assessment of isolates of mangroves or mangrove associates shows potential value for at least one pharmaceutical or food processing application. One key characteristic of said 'bioactives' is their increased efficacy when extracted using organic rather than aqueous solvents, suggesting potentially greater usefulness than currently observed under the predominantly aqueous traditional extraction pathways.

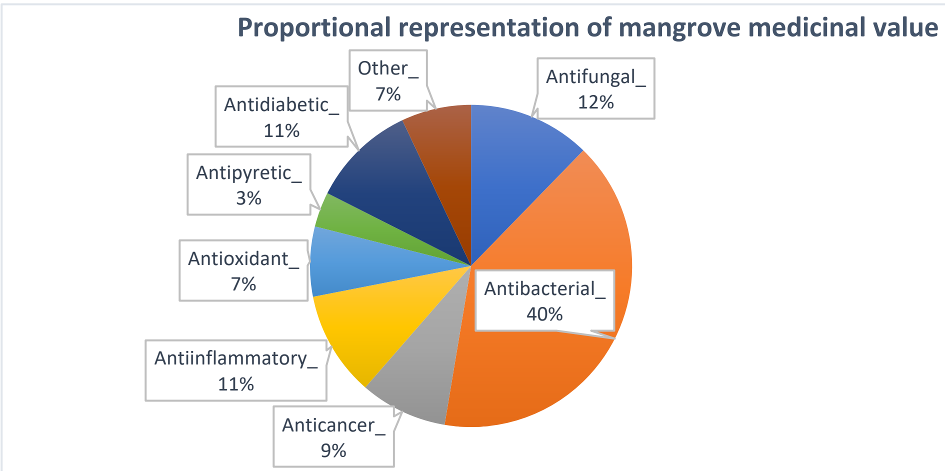

Figure 11: Proportional representation of reported medicinal properties of mangrove bioactive compounds.

Antagonistic action was reported in a wide variety of proportions (Figure 11). Antifungal ability was evident in only actinobacterial and endophytic fungal associates of mangal, whereas antipyretic and antioxidant action was seen in plant and plant associates only. Endophytic fungi and mangrove plants were the two sources of reported metabolites with anti-inflammatory abilities (Figure 12).

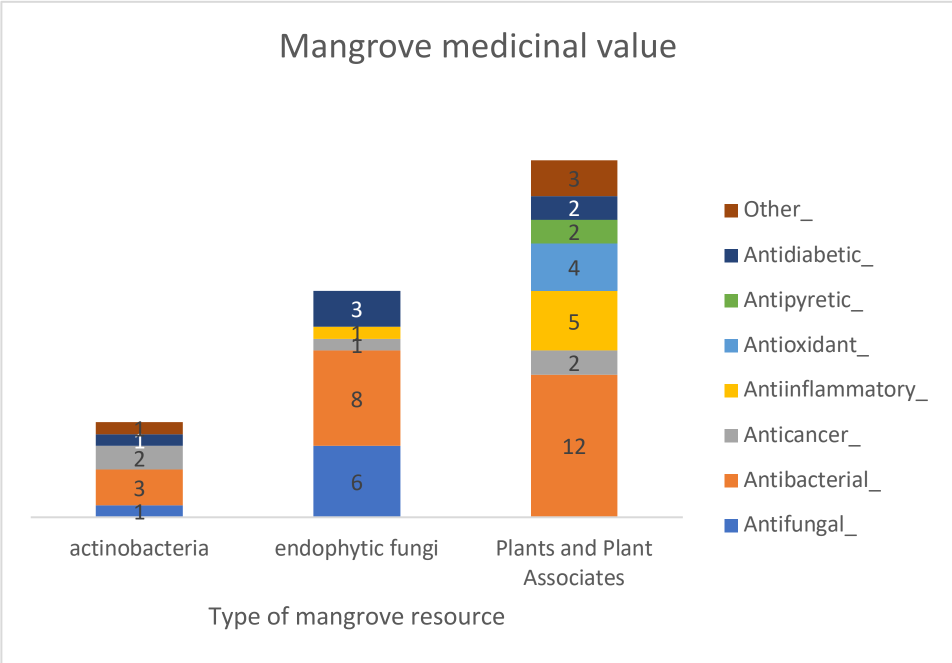

Figure 12: Respective number of records reporting diverse biological activity for different mangrove resource types.

Like others of the larger plant kingdom, mangrove extracts have been used for their anti-tumour abilities. They have been shown to possess the chemical compounds that exhibit cytotoxic effects on cancer cells, including phenylpropanoids and terpenoids (Trapp and Croteau, 2001). The evidence supplied by Azman et al. (2017) and Hong et al. (2009), suggest that anticancer properties of mangrove extracts were demonstrated in the form of gene expression inhibition, cell cycle arrest and apoptosis of cancer cell lines. Whereas Azman et al. detected antagonistic action against cervical cancer cells of the 'Ca Ski' cell line, Hong et al observed antitumor activity against colon cancer '116' type cells as well as 'Aurora Kinase A' protein inhibition, which leads to more effective apoptosis (immunological destruction) of cancer cells. These two studies were conducted on extracts of actinobacteria sourced from mangrove ecosystems, but comparable results were reported for extracts of mangrove plants as well. Sari et al., (2018) for example, also observed induction of apoptosis and cell cycle alterations in colon cancer cell lines and concluded that the *Rhizophora* and *Ceriops* extracts tested hold promise for the development of anticancer agents. In Ramalingam and Rajaram (2018), A549 lung cancer cells were found to be similarly susceptible to organic extracts of *Rhizophora spp.*

3.3.1.2.1 Antidiabetic Action

Antidiabetic action of extracts of mangrove and mangrove associates reported in this review lies chiefly in their inhibitory activity against enzymes (α-glucosidase, α-amylase) involved in glucose metabolism at the cellular level (Nathiya and Mahalingam, 2018; Lopez et al., 2015; Lopez et al., 2018; Lopez et al., 2019). Lopez et al., (2018) in particular, highlight the outstanding therapeutic value of Panamanian mangroves, given the fact that 60% of the mangrove extracts studied showed α-glucosidase inhibitory activity. Work done by Ai et al., (2014) and Hong et al., (2009) alternatively described inhibition of another diabetes-related protein (tyrosine phosphatase 1B -PTP1B), representing about 3% of the investigated actinobacterial isolates in the latter. One limitation, in respect of these inhibitory actions, lies in the fact that these studies were conducted in-vitro, which leaves the questions of toxicity and concomitant cell or tissue effects unanswered. The only exception was Ai et al., who specifically concluded that the chief compound analysed demonstrates promise for diabetes treatment without toxic side effects. Taken together, the results of these assessments validate the traditional use of these mangrove derivatives against hyperglycaemia.

3.3.1.2.2 Antioxidant Action

Mangrove ecosystems are characterised by extraordinary conditions of frequent inundation, anaerobic mud, and high salinity among others (Macintosh and Ashton, 2002). Due to these environmentally stressed conditions that mangrove plants are adapted to, they exhibit unique antioxidant mechanisms that enable them to scavenge free-radicals and protect the plants from destructive reactions (Patra and Thatoi, 2011). This property is often transferred to their aqueous and organic extracts.

Suganthy et al., (2009) and a few other authors allude that free-radical mopping ability of mangrove derivatives, which confers antioxidant properties, increases with increasing phenolic content (Suganthy et al., 2009; Patra et al., 2011; Hamzah et al., 2018; Islam et al., 2020). Such properties protect cells and tissues by averting the chain reactions that lead to oxidative stress and damage. For example, nitric oxide synthases, enzymes which produce the potentially oxidative cellular signalling nitric oxide, can be inhibited especially by methanolic stem and leaf phenol extracts especially of *Rhizophora,* *Avicennia, Bruguiera, Deris, Suaeda and Xylocarpus* spp. Chi et al., (2019) and Ravangpai et al., (2011) report of antioxidant action of this nature for mangrove endophytic fungi and seed extracts, respectively. Chi et al. show that higher anti-inflammatory action is accompanied by lower cell viability for the isolates analysed, raising questions about tolerance levels and toxicity.

3.3.1.2.3 Anti-Inflammatory Action

Anti-inflammatory effects, expressed in the form of protection against complex biological responses to harmful stimuli (e.g., pathogenic attacks or injury) was reported in this present review, but to a lesser extent than antimicrobial action (Roome et al., 2008; Shilpi et al., 2012). In Islam et al., (2020) leaf and bark extracts of *Heretia fomes* mangrove demonstrated significant anti-inflammatory activity, although not as strong as diclofenac sodium anti-inflammatory drug. Barik et al., (2016), in reporting on similar anti-inflammatory action of leaf extracts of *Bruguiera spp*, concluded that modulation of oxidative stress, coupled with arachidonic acid inflammatory cytokine inhibition, could be the mechanisms of action. The strongest evidence of anti-inflammatory potential is supplied by Eldeen et al, (2019), with 75% - 96% inhibition of inflammatory enzymes reported for leaf and root extracts of same *Bruguiera spp,* including remarkable absence of associated cytotoxic effects.

3.3.1.2.4 Anti-Microbial Action

Strong and broad-spectrum antibacterial action, including against human pathogenic bacteria, has been previously attested for several mangrove species (Bandaranayake, 2002). In the present review, antibacterial property was the most reported (40% of studies) for mangrove ecosystem secondary metabolites (Figure 11). This antibacterial action was established against most human pathogenic microbes, such as faecal coliforms that cause gastroenteritis (e.g., *E. coli*), agents of food spoilage (e.g., *Streptococcus spp*.) and those responsible for urinary tract infections which affect over 50% of adults in their lifetime (dos Santos et al., 2010; Devi et al., 2014). Simlai et al., (2016) detected inhibitory properties in wood extracts of *Ceriops decandra* against 9 bacteria strains, 6 of which are pathogenic to humans. Likewise, Simlai et al. (2014) and Yompakdee et al. (2012) report on stable antagonistic activity against both gram-positive and gram-negative bacteria, indicating potential suitability of *Sonneratia caseolaris* extracts for pharmaceutical and food processing applications. The study by Buatong et al., (2011) revealed that up to 61% of the endophytic fungal isolates possess antimicrobial properties, including inhibitory action against *Candida albicans* fungus. Expectedly, the familiar and competent antibiotic *Penicillium spp* of fungi produced the most potent inhibitors of *Salmonella typhi* bacteria in the work done by Rossiana et al (2016).

Few of the pathogens tested were strains that are multi-resistant to current antibiotics. One fungal extract analysed in Kjer et al., (2009), and 50% of the studied actinobacterial extracts in Jiang et al., (2018) for example, exhibited significant broad spectrum antibacterial action, including against resistant strains. Apart from the intrinsic value of biodiversity in mangrove ecosystems, this signifies promise of novel drugs that could address the growing worldwide antibiotic resistance menace.

3.3.1.3 Other Findings

Human and plant pathogenic viruses, such as those responsible for tobacco mosaic, HIV-AIDS, and hepatitis B, have in the past been described to be susceptible to mangrove plant extracts, particularly of *Rhizophora* spp. (Premanathan et al., 1999). This was not captured in any of the findings of this current review. A series of further suggested bioactivities reported in other appraisals, such as antifeedant, antiulcer, antifouling and nematocidal abilities (Patra and Thatoi, 2011) did not show up in the present review either. The least reported properties, collectively designated as 'other', were antiparasitic (against *Plasmodium spp*., *Trypanosoma spp*.,) (Lopez et al., 2015) and neuroprotective action (Azman et al., 2017) described for actinobacteria, plant and plant associates (Figure 12). While not all chemical isolates analysed demonstrated bioactive properties, every paper reported at least one desirable health-promoting attribute of the mangrove-derived compounds assessed, as catalogued in Table 6.

Table 6: Medicinal Properties of Mangrove Plants and Mangrove Associates

TYPE OF MANGROVE RESOURCE	PAPERS	SPECIES	PURPOSE	KEY FINDINGS
ENDOPHYTIC FUNGI	(Nurunnabi et al., 2018)	*Heritiera fomes*	Assessment of cultured fungal associates to validate use in folk medicine	Antibacterial activity demonstrated against *E. coli* for all organic extracts except for ethyl acetate derivative
	(Nathiya and Mahalingam, 2018; Chi et al., 2019)	*Avicennia marina, Acanthus ilicifolius, Rhizophora mucronata and Rhizophora apiculata*	Antidiabetic and anti-inflammatory activity evaluated	Anti-inflammatory, α-glucosidase, and α-amylase inhibitor action demonstrated. Varying cytotoxicity observed, indicating the safer option. The higher the enzymatic inhibition of nitric oxide synthase (i.e., anti-inflammatory activity), the lower the viability of treated cells.
	(Hamzah et al., 2018)	*Rhizophora mucronata*	Isolation and screening of 74 fungal associates from the leaf tissue	Antimicrobial activity against pathogenic bacteria exhibited by one, and free radical scavenging ability by another
	(Meng et al., 2015)	*Avicennia marina*	Analysis of antimicrobial and cytotoxic activity	Some antimicrobial activity detected
	(Zhang et al., 2019)	*Bruguiera gymnorrhiza*	Bioassay of metabolites of mangrove-derived endophytic fungi	Anti-microbial activity against human and aquatic bacteria as well as plant pathogenic fungi Mixed results. Inhibitory action against some but not others.
	(Kjer et al., 2009)	*Sonneratia alba*	Characterization of endophytic fungi extracts	Anti-bacterial and antifungal activity detected. Two novel compounds exhibited weak antibacterial activity against staphylococcus aureus. Another compound showed broad antimicrobial activity against several multidrug-resistant bacterial and fungal strains
	(Buatong et al., 2011)	Various	assessment of 150 isolates	Anti-bacterial and anti-fungal action produced by 63% of inhibitory compounds. Varied action against human pathogenic bacteria and *Candida albicans*, including broad spectrum
	(Rossiana et al., 2016)	*Rhizophora apiculata Bruguiera gymnorrhiza*	Assessment of antibacterial activity against *Salmonella typhi*	Anti-bacterial action exerted by isolated *Penicillium spp.* which had the most significant activity.
	(Ai et al., 2014)	*Kandella candel*	Assessment of antimicrobial, anticancer and antidiabetic properties	Anti-cancer and anti-diabetic action. 2 isolates had cytotoxic activity against 10 human tumor cell lines. 1 isolate had inhibitory action against two key enzymes targeted in treatment of diabetes
	(Ling et al., 2016)	Various, plus Mangrove sediment	Assessment of antimicrobial activity and heavy metal remediation potential	Antibacterial and antifungal activity strongly shown in 2 out of 12 isolates. Maximum Heavy metals bio absorption by 2 species
	(Lopez et al., 2019)	*Laguncularia racemosa*	Assessment of α-glucosidase activity of *Zasmidium spp*. isolate	Anti-diabetic action. Strain has bioactive contents that have beneficial properties (91.3% inhibition) for diabetes control and human health
ACTINOBACTERIA	(Li et al., 2019)	Mangrove soil	To explore pharmaceutical potential	Antagonistic activity against selected bacteria by 54 isolates shown
	(Jiang et al., 2018)	*Avicennia marina Aegiceras corniculatum Kandelia obovota, Bruguiera gymnorrhiza,* and	Screening of endophytic actinobacteria	Promise of antibacterial activity exhibited by 31 out of 63 cultivable strains, including against some resistant pathogens

TYPE OF MANGROVE RESOURCE	PAPERS	SPECIES	PURPOSE	KEY FINDINGS
		Thespesia populnea		
	(Azman et al., 2017)	*Mangrove Soil*	Extraction of bioactive compounds from 3 novel associates for antibacterial, anticancer, and neuroprotective activity	Bacteriostatic activity in all extracts Anticancer activity in 1 strain against cervical cancer cell lines Varied neuroprotective action demonstrated in 3 extracts
	(Hong et al., 2009)	Various	Isolation and characterization of actinomycetes from mangrove soil and plant material in China	Over 2000 isolates 20% - Human colon tumour cell inhibition 5% - Candida albicans inhibition 10% - *Staphylococcus aureus* inhibition 3% - Diabetes-related protein inhibition
PLANTS AND PLANT ASSOCIATES	(Ramalingam and Rajaram, 2018; Sari et al., 2018; Gopal et al., 2019)	*Rhizophora spp.*	Evaluation aqueous and organic leaf, stem, bark, and root extracts of plant species to verify antimicrobial, anti-inflammatory, anti-cancer and	Anti-microbial action in bark extracts particularly efficient against human pathogenic bacteria. Organic extracts (mainly methanolic or chloroform) are the most effective. Some excellent antioxidant activities. Apoptosis, gene expression inhibition and cell cycle arrest were observed in varying proportions in anticancer studies
	(Audah et al., 2018; Eldeen et al., 2019; Barik et al., 2016)	*Bruguiera spp.*	Used traditionally to treat burns, inflammatory lesions, high blood pressure, haemorrhage, and ulcers. Antimicrobial and anti-inflammatory assessments of root, wet and dry leaf extracts.	Anti-bacterial action detected. Ethanol extracts were most potent against *E. coli* and S. aureus. Wet leaf extracts had more efficient antimicrobial activity. Strong anti-inflammatory properties, including modulation of oxidative stress found in methanol extracts
	(dos Santos et al., 2010; Devi et al., 2014)	*Avicennia spp.*	Bioassays of leaf, root, and bark extracts for antimicrobial properties	Anti-microbial activity. Roots extracts most efficient, leaf extracts potent against pathogens that cause urinary tract infections which affect over 50% of humans in their lifetime
	(Simlai et al., 2014; Yompakdee et al., 2012)	*Sonneratia spp.*	Antimicrobial and anti-oxidative assessment of leaf, root, and bark extracts to understand folkloric use as astringent and antiseptic agent	Activity exhibited against both gram-positive and gram-negative bacteria for the methanol extracts but not as significantly for others. Clinical, food-processing, and pharmaceutical potential established
	(Ravangpai et al., 2011; Hasan et al., 2019)	*Xylocarpus spp.*	Investigation of antinociceptic and anti-inflammatory properties to validate traditional use	Anti-inflammatory activity, due to inhibition of nitric oxide production by macrophages detected. Rare in-vivo demonstration of 49%-68% pain reduction and inhibition of inflammatory response.
	(D'Souza et al., 2010; Saad et al., 2011)	*Lumitzera spp.*	To investigate antimicrobial activities of organic extracts of plant	Antimicrobial activity detected against gram-positive bacteria, which increases with increased extract concentration. No effective action against fungi and viruses
	(Bose and Bose, 2008; Wei et al., 2015)	*Acanthus ilicifolius*	Evaluation of organic leaf extracts to understand use in asthma and	Moderate to high antibacterial and antifungal activity, protective effect on liver tissue and therefore preservation of liver function. No inhibition of duck hepatitis B virus

TYPE OF MANGROVE RESOURCE	PAPERS	SPECIES	PURPOSE	KEY FINDINGS
			rheumatism treatment	
	(Islam et al., 2020)	*Heritiera fomes*	Antioxidant and anti-inflammatory potential of *Heritiera fomes* bark extract assessed in comparison to diclofenac sodium and indomethacine	Significant antioxidant and anti-inflammatory activity present
	(Simlai et al., 2017)	*Deris trifoliata*	In-depth phytochemical assay of stem tissue	Stable antibacterial and antioxidant activity observed, especially for the methanolic extract, under varied pH and thermal conditions.
	(Simlai et al., 2016)	*Ceriops decandra*	Purification and characterization of wood extract	Inhibition of 9 micro-organisms, 6 of which are pathogenic.
	(Patra et al., 2011)	*Suaeda maritima*	In-vitro Investigation of antioxidant and antimicrobial actives of aqueous and organic extracts	Strong antioxidant properties, free-radical, metal, and nitrous oxide scavenging activity and ascorbic acid content in both leaf and stem extracts had. Selected organic extracts showed inhibitory activity against some pathogenetic bacteria, using amoxicillin as standard.
	(Roome et al., 2008)	*Aegiceras corniculatum*	To investigate traditional use for treating inflammatory diseases	Anti-inflammatory activity significantly shown In-vivo and in-vitro, validating traditional use
	(Lopez et al., 2015)	*Pelliciera rhizophorae*	Evaluation of species potential as source of bioactive compounds to validate traditional medicinal use in Panama	Antiparasitic activity against *Trypanosoma cruzi* and *Plasmodium falciparum* Better inhibition of α-glucosidase enzyme than anti-diabetic drug acarbose
	(Neamsuvan et al., 2015; Lopez et al., 2018; Suganthy et al., 2009)	Various	Evaluation of general medicinal use. investigation of antiparasitic, anticancer, antimicrobial, free-radical scavenging, and hypoglycaemic properties of organic extracts	Widespread use identified, including for antipyretic purposes. Demonstration of varying degrees of antibacterial and antioxidant activity, which increases with increasing phenolic content. In one case, no antibacterial activity was demonstrated against 7 food-borne pathogens studied. In another instance, 60% showed alpha glucosidase inhibitory activity, suggesting presence of hypoglycaemic compounds. One species had moderate activity against *Plasmodium* falciparum. No extract showed anticancer activity

3.3.2 REGULATION OF SEDIMENT AND AQUATIC CHEMISTRY

3.3.2.1 Background

A growing abundance of evidence confirm the adverse effects of anthropogenic chemicals on the ecological conditions of mangroves (Lee, 2008; Duke et al., 2000). Bioaccumulation pathways and toxicity are also described in the literature with regards to mangroves and their associated biota (Lewis et al., 2011) (Figure 13). Saenger et *al*, (1991) for example, detail how physical and biogeochemical barriers in mangrove ecosystems act as interventive mechanisms for contaminant filtration. Left unchecked, trace metals have the capacity to bioaccumulate in mangrove plant and fauna tissues, posing health risks to consumers in high concentrations. Although rarely studied in relation to mangrove ecosystems, mercury in the form of methyl mercury for instance, is crucial for its effects on neural development in humans (Kehrig et al., 2003). While a few studies, such as Macfarlane, (2002) have probed the effects of mercury bioaccumulation on mangrove plant physiology and survival, little work appears to have been done in terms of linkages to health of nearby dependent human populations.

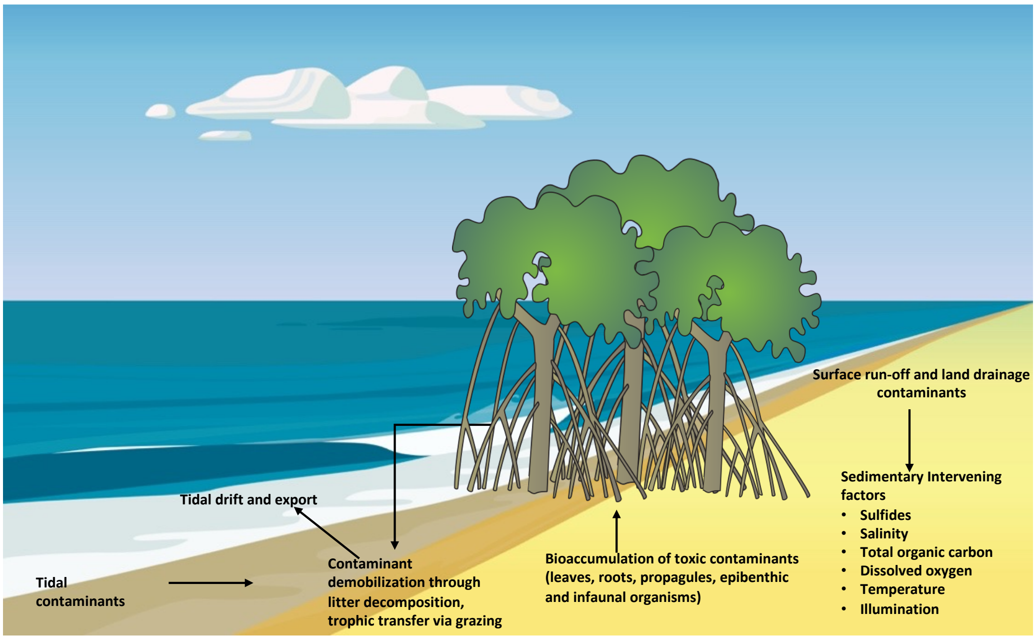

Figure 13: Pathways for Contaminant Toxicity and Bioaccumulation in Mangrove Ecosystems, adapted from Lewis et al., (2011)

The fine grains of mangrove sediments are known to sequester up to 22 trace metals, with copper, zinc and lead being the most reported (Tam and Wong, 1997; Lewis et al., 2011). For this reason, sediment chemical contaminants have often been assessed alongside that of water and biota, using different parameters, to ascertain bioconcentration dynamics and toxicological risk to health (Cuong et al., 2005; Defew et al., 2005; MacFarlane and Burchett, 2000; Melville and Pulkownik, 2007). While mangroves are more tolerant of trace metals, they are more susceptible to oil spills. This is because oil spills interfere with pneumatophore activity, which hinges on sheer tree survival, as well as being the primary adaptation for detoxifying contaminants and excluding ions in the first place (Walsh et al., 1979). Organic chemicals such as petrochemicals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAH) concentrations in mangrove sediments have been studied for their neurological and carcinogenic toxicities and varying adverse biological effects in human populations. (Tam and Yao, 2002; Cavalcante et al., 2009).

3.3.2.2 Findings

3.3.2.2.1 Heavy and Trace Metal Remediation

Mangrove roots act as barriers preventing free heavy metal movement to more sensitive parts such as leaves (Kathiresan and Bingham, 2001) (Figure 14). Concentrations of metal contaminants decrease from root to stem to leaves in that order (Tam and Wong, 1997). Iron plaques formed by oxygen released via underground roots prevent excessive uptake of heavy metals into root cells. Coupled with the fact that physico-chemical properties of the typical mangal sedimentary environment traps trace metals in biologically unavailable form, heavy metal contamination can thus be effectively excluded from mangrove tissue. According to Kathiresan and Qasim, (2005) anoxic conditions of mangrove sediments enable the formation of metal sulphides and organic complexes that bind heavy metals and make them less bioavailable. Reduced bioavailability of heavy metals in the mangrove environment, resulting from the stated ecosystem processes, reduces the risk of bioaccumulation in edible micro and macro fauna of the mangrove food chains. Figure 14 demonstrates the biochemical processes in mangal ecosystems that make them effective mediators of trace metal pollution, except for the most mobile forms such as Mn and Zn (Lacerda, 1997).

Provided sediment binding capacity is not exceeded by excessive pollutant load, the pollution intervening mechanism of mangrove ecosystems can reduce ecological and health risks within the mangrove environment (Stigliani, 1995). Disturbances in the form of the climate-related changes in precipitation and flooding (and therefore salinity), which affect ecosystem integrity, can re-mobilize metal pollutants (Lacerda, 1998) with consequences for human health.

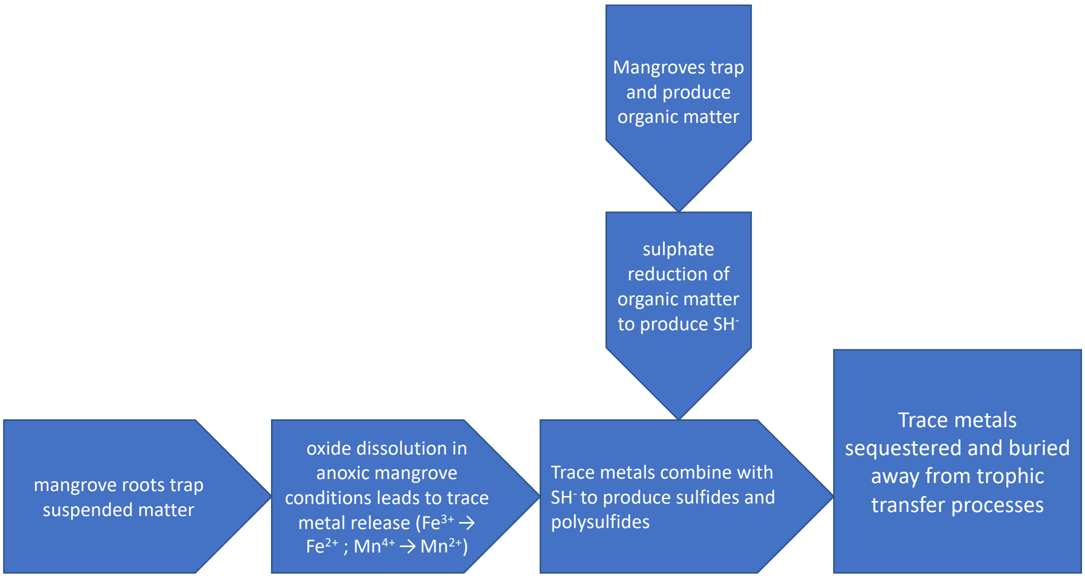

Figure 14: Major Anoxic Metabolic Processes in Mangrove Sediments Involving Metals (Kathiresan and Bingham, 2001)

In the current review, heavy/trace metal pollution was discussed in the contexts of long-standing concern about pollutant accumulation within mangrove ecosystems, seen as waste reservoirs for surface, domestic and industrial run-off. In most cases, metal content of mangrove-sourced food was analysed as a proxy indicator of bioaccumulation magnitudes, and therefore the effectiveness of bioremediation processes of the ecosystem. The results indicate that despite regular subjection to heavy contaminant load, mangroves provide significant bioremediation services that minimise risks of heavy metals to human health.

Out of 27 papers pertaining to heavy and trace metal remediation captured within the current review, only De *et al*., (2010) did not indicate some pollutant remediation effect of the mangrove ecosystem (Figure 15). The authors concluded that although occasional consumption posed no harm, 7 days of successive ingestion would be risky to health of consumers of fish from an Indian mangrove. Apart from that account, for every report of moderate or conditional pollution attenuation, there were two undeniably positive effects of mangroves on pollution outcomes for the aquatic or sediment environment.

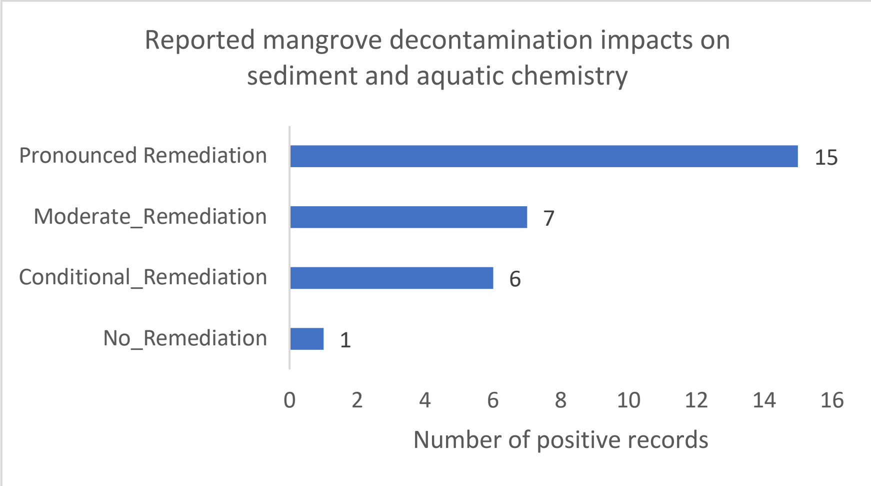

Figure 15: Reported Nature of pollution remediation effects of mangroves

Toxic enrichment from anthropogenic discharges into mangrove ecosystems have constituents including As, Hg, Cr, Pb etc. These heavy metal pollutants are readily ingested by intertidal organisms, some of which are consumed in abundance by humans. Liu et al, (2014) indicate that mangrove food resources such as molluscs and fish could be potential heavy-metal hazards to humans. Heavy metal ingestion via mangrove food consumption was the subject of the analysis conducted by Cheng and Yap (2015). In their study, mangrove snails *Nerita lineata* soft tissue and surface sediments were analysed for As, Cd, Cu, Cr, Hg, Pb and Zn. Results indicated low ecological risk (PERI[35]) Values, which denote potential risk to consumers' health (Hakanson, 1980). EDI[36] values were also generally lower than the reference dose (RfD-daily tolerance dose that poses no deleterious effects, (Barnes et al., 1988)). Also, hazard quotients (THQ[37]-ratio of dangerous vs. safe exposure levels) were less than 1 for low level consumers, which indicates no adverse health effects.

Some of the assessments, such as Aziz et al., (2018), and Wang (2010), further suggest suitability of the mangrove ecosystem as a bioremediation tool for maintaining estuarine water quality, with natural and restored mangroves being observed to hold similar promise according to Li et al., (2016) and Boonsong et al., (2003). Peng et al.,

[35] Potential Ecological Risk Index
[36] Estimated Daily Intake
[37] Target Hazard Quotient

(2013) specify that this purifying function is extended to aquaculture ponds associated with mangroves, resulting in better self-purification of those synergistic systems. Two of the studies, (Nguyen et al., 2019; and Le et al., 2017) cite elevated contaminant levels, and abnormally higher consumption of mangrove foods (especially of species higher up food chains), as conditions that potentially undermine mangrove pollution mediating services. In a comparative assessment conducted by Li *et al* (2016), the unique causative role played by mangroves was demonstrated by decreasing Hg and Cu extraction capacity from mangrove to non-mangrove ecosystems subject to similar pollutant levels. Additionally, Analuddin *et al*.,(2017) establish how higher diversity of mangrove plants further amplifies this positive bioremediation service. Higher diversity of mangrove vegetation thus seems to promote more effective heavy metal exclusion, leading to better health outcomes for consumers of associated food products.

In the review by Lewis et al (2011), most of the studies on heavy metal detoxification activity of mangroves report on bioaccumulation in sediments, roots, and leaves; with the salt glands of leaves cited as major excretory pathways. Thus, mangroves can filter out some toxic materials from reaching marine species, including fisheries used as food. Some studies such as Naidoo *et al*., (2014), which report comparable results, however, indicate that mangroves may not necessarily be ideal phytoremediators, due to them not being comparatively hyper accumulators of heavy metals. The writers further assert that sequestered elements are eventually released into the environment through decay of dead plant matter. Metal-dependent differences in results are also likely, although not specifically investigated in this review.

3.3.2.2.2 Hydrocarbon (Organic) Pollutant Control

Mineral nutrients like nitrogen and phosphorus are readily absorbed in mangrove topsoil, where they could then be metabolised by microbe communities, with phosphorus being more readily absorbed from wastewater than nitrogen (Tam and Wong, 1995). On the other hand, patterns of water flow via the mangrove ecosystem, which affect both flushing rates and residence time, determine the tolerance of mangal for organic pollutants. Recovery of mangrove ecosystems from oil pollution tends to happen more slowly, if at all. The effects of an oil spill a mangrove area in Brazil for example, were not overturned until after a decade (Lamparelli et al., 1997).

Urban run-off, oil spills, industrial effluents and atmospheric pollutants are sources of toxic hydrocarbons that end up in mangrove ecosystems (Bashir et al., 2017). Mangrove response to PAHs has remained a curious interest for researchers due to impacts that include plant cell damage, and therefore growth reduction and mortality, morphological and physiological damage, and photosynthetic interference (Naidoo and Naidoo, 2017). Some species of mangrove plants, such as *A. marina* and *R. mucronata*, which develop pneumatophores with wide sediment-root interface, may suffer consequences of PAH accumulation in root tissue. Apart from contributing to tree death, PAHs have also been implicated in health problems in nearby terrestrial and aquatic communities through food web transfers (Wang et al., 2014).

One paper captured in this review, Aziz et al. (2018), studied the mangrove ecosystem supported co-metabolism process that transforms toxic PAH contaminants into non-toxic forms through microbial action. Analysing a consortium of bacterial isolates from Malaysian mangrove sediments, the researchers probed the bioremediation effects of biodegradation of Benzo-a-Pyrene (BaP), an organic PAH with carcinogenic and endocrine disruptive competence. They concluded that the analysed collection of mangrove microorganisms is effective at biologically degrading benzopyrene PAHs under the unique saline conditions of the mangal environment, especially at the 30^{o}C optimal temperature typical of the tropics. Tropical mangroves thus, in the long term, support the ecological processes which potentially assuage the harmful health risks associated with widespread and persistent PAH contaminants like benzopyrenes.

Santos et al., (2020) focused on PCB remediation in a Brazilian mangrove ecosystem, where no significant health risks were associated with consumption of exposed fish and shellfish. Furthermore, the authors opined that anthropogenic PCB contamination levels within mangrove bays investigated were markedly and comparatively lower than that of other non-tropical bays. This indicates how the biota and seafood of the mangrove environment in that location pose less of a risk to human health than in other regions. Equivalent results are reported in Bodin et al., (2011) (Table 7).

Table 7: Pollution Mediating Action of Mangrove Ecosystems

PAPER(S)	LOCATION	PURPOSE & TARGET(S) OF ANALYSIS	KEY FINDINGS
(RUMISHA ET AL., 2016)	Tanzania	Trace metals in 60 sediment and 160 giant tiger prawn samples to document distribution and potential threat to mangrove fauna and public health	As, Cd, and Hg present moderate risks to fauna. Elevated levels of Cu, Fe and Zn were observed in prawns. Level of the non-essential Cd, Hg, and Pb did not exceed maximum allowed levels for human consumption.
(ANALUDDIN ET AL., 2017)	Sulawesi, Indonesia	Role of mangroves as a biofilter of heavy metals	Variety of trends in translocation and bioaccumulation factors. High mangrove plant diversity ensures health and productivity of coastal zones
(DE VALCK AND ROLFE, 2018)	Great Barrier Reef, Australia	Estimation of loss of benefits to society resulting from water quality reduction, influence of pollutants on ecosystem services of mangroves, seagrass, and coral reefs	Provisioning, regulating, and supporting ecosystem services from mangroves are crucial to well-being. Failing to meet the Government's water quality targets by 1% would result in losses between AU$22 k/year and AU$6.9 M/year depending on the industry
(LING ET AL., 2016)	Malaysia	Characterization of plant and soil endophytic fungi and their antimicrobial production and bioremediation potential for heavy metals (Cu and Zn)	Mangrove endophytic fungi produce bioactive compounds and have promising potential for the purification of heavy metal-contaminated wastewater
(NAIDOO ET AL., 2014)	South Africa	Soil retention and root ultrafiltration capacity to exclude trace metals via leaf salt glands of *Avicennia marina*	Salt glands of this mangrove species contribute to eliminating at least part of physiologically essential trace metals if taken up in excess
(PENG ET AL., 2013)	South China	Evaluation of combined mangrove conservation and aquaculture targets via assessment of water quality impacts of Integrated Mangrove Aquaculture System (IMAS)	Aquaculture ponds can become self-purifying through nutrient uptake by the mangrove, increasing harvests of some mangrove-dependent species increased by over 10%
(TAN ET AL., 2018)	China	Choice experiment to value the environmental improvements in coastal wetland restoration	People valued the positive benefits of coastal wetland restoration, particularly water quality improvement potential. The mangrove area had the highest marginal 'willingness to pay' value.
(VAN OUDENHOVEN ET AL., 2015)	Java, Indonesia	Effects of different management regimes on mangrove ecosystem services (food, raw materials, coastal protection, carbon sequestration, water purification, nursery, and nature-based recreation)	Natural mangroves scored highest for most services, except for food
(WANG ET AL., 2017)	China	Evaluation of ecological service value of the mangrove forest using a market value method, an ecological value method and a carbon tax method	The indirect value of disturbance regulation, gas regulation, water purification, habitat function and culture research reached 14,719,000 CNY/a, with a ratio of 91.4%
(WANG ET AL., 2010)	China	Measurement of seasonal changes in water quality for samples taken at various distances from shallow water across mudflat to mangroves	Results support the hypothesis that the maintenance of estuarine water quality by mangroves occurs during flood periods
(BORRELL ET AL., 2016)	Bangladesh	Zn, Cu, Cr, Hg, Pb, Cd and as levels in 14 plant and animal species from mangrove forests used for food, were analysed for trace element transfer through the food chain	Fish and crustaceans were deemed safe for consumption by international standards, except for one species of each, which had concerning levels of Cr and Cd; and, Zn, respectively
(BODIN ET AL., 2013)	Senegal	Inorganic sediment and mollusc contamination in mangrove ecosystems	Strong differences in trace metal bioavailability and bioaccumulation, but levels were below threshold limits for 'adverse biological effects'

PAPER(S)	LOCATION	PURPOSE & TARGET(S) OF ANALYSIS	KEY FINDINGS
(LI ET AL., 2017B)	China	Heavy metal analysis of water, sediments, and edible molluscs from mangrove wetland	Varied bioaccumulation abilities in edible molluscs, sediment levels of Cd and Zn were lower than safety threshold, THQ show potential risk to consumers, but no harmful effects at daily intake quantities
(LI ET AL., 2016)	Shenzhen, China	Core natural mangrove sediment analysis to investigate mangrove influence on heavy metal accumulation and storage	Hg and Cu accumulation competence decreased from natural to restored mangrove, and then again to mud flat, indicating mangrove influence in heavy metal exclusion from aquatic environment
(MARTINEZ-SALCIDO ET AL., 2018)	California, USA	Hg-related human health risk from muscle and liver analysis of edible mangrove lagoons fish	None of the fish had Hg THQ that was risky to human health
(NGUYEN ET AL., 2019)	Vietnam	Assessment of distribution of Fe, Mn, Cu, Co, Ni Cr, As in tissues of mangrove plants and edible snail.	Level of contamination, sediment geochemistry and specific specie requirements influence tissue accumulation. Fe, Mn, and Cu most dominant in snail tissue; As high due to snail uptake and metabolization capacity
(AZIZ ET AL., 2018)	Malaysia	Benzo pyrene (PAH) digestion potential investigated for a consortium of mangrove sediment bacterial isolates	Natural biodegradation activity confirmed, indicating capacity for use in seawater bioremediation to reduce human health risks.
(BODIN ET AL., 2011)	Senegal	PCB concentrations in sediments, bivalves and gastropods examined for their human health risk	Concentrations from various assays showed no potential human health risk form shellfish consumption
(BOONSONG ET AL., 2003)	Thailand	Planted *Rhizophora, Avicennia Bruguiera and Ceriops* mangrove plant species evaluated for their wastewater purification capabilities	Constructed mangrove wetlands can attenuate wastewater pollution risk in a comparable way as natural mangroves
(CHENG AND YAP, 2015)	Malaysia	Edible mangrove snails *Nerita lineata* soft tissue and surface sediments analysed for As, Cd, Cu, Cr, Hg, Pb, Zn	Low ecological risk (PERI values). Estimated daily intake values lower than the RfD, THQ less than 1 for low level consumers.
(COSTA ET AL., 2018)	Brazil	Individual consumption health risk assessment of Pb in edible mangrove crab *Goniopsis cruentata*	THQ less that 1, indicating negligible risk to human health through use as food
(DE ET AL., 2010)	India	Levels of Cu, Zn, Ni, Cd, Cr and Pb in edible fish assessed for a mangrove dominated estuary	PTWI per kg body weight values were marginally high, posing a health risk in 7-day successive consumption scenario
(KANHAI ET AL., 2014)	Trinidad and Tobago	Presence and potential impact of Cd, Cr, Cu, Ni, Pb and Zn in mangrove sediments and oysters	Low and minimum ecological risk based on Canadian sediment quality guidelines. Zn levels potentially unsafe to health of oyster consumers
(LE ET AL., 2017)	Malaysia	Hg bioaccumulation assessment in edible finfish for human health risk	Health concern for carnivorous species consumption; overall trans-trophic assessments indicate minimal risk based on PTWI
(LI ET AL., 2017A)	Dongchaigang, China	Seawater, sediment, and mollusc heavy metal levels assessed for health risk	Only Zn and Cd levels low in sediments, heavy metal contamination of molluscs high, although THQ suggests no harmful effects on humans
(SANTOS ET AL., 2020)	Brazil	Examination of mangrove shellfish for PCB contamination	5 out of 12 species showed PCB presence, but levels lower than other regions around the world. No risk to human health through consumption as food.
(SHI ET AL., 2020)	Shenzhen, China	Assessment of distribution, pollution levels and human health risks in urban mangrove sediments	Levels highest in locations closest to point source discharges, little adverse public health risk from exposure to Hg

3.3.3 MANGROVES AND HUMAN NUTRITION

3.3.3.1 Background

The main links between mangrove ecosystems and the provision of goods that support human nutrition, can be found in the combined mediation of aggravated bioaccumulation of harmful substances, and the habitat support services for fisheries. High productivity of mangroves ecosystems, which translates into energy for detritus-based food chains, benefits biomass and nutrient build up mechanisms in food chains. Finally, as pointed out by Beck et al. (2001) and Lee (1999), mangroves provide conducive aquaculture conditions, critical nursery, and retention grounds for fisheries larvae, as well as predation refuge for their juvenile forms. By helping fisheries populations to flourish, these mechanisms ensure that the nutritional needs of consumers including humans higher up the food chain, are met.

Mangrove fungi and bacteria are responsible for the decomposition processes that help to achieve high dissolved organic matter content in otherwise low-nutrient tropical waters, to the benefit of fisheries. According to Kathiresan and Bingham (2001), greater inundation and feeding activities of invertebrates are some conditions that facilitate faster litter decomposition. Mangrove detritus appears to make more of a localised contribution to food webs, with its importance being greater as a microbial substrate than as a direct food source (Wafar et al., 1997). These unique services together, under optimal conditions, would eventually enable protein nutritional needs to be met.

Although the causal importance of mangroves in shoring up nurseries support functions remains contested (Nagelkerken et al., 2008; Halpern, 2004; Heithaus et al., 2011; Shahraki et al., 2014), the connectivity of marine ecosystems to mangroves has been established as a key booster of overall fisheries productivity. Alternatively put, while the evidence does not necessarily point to mangroves being the sole backbone of associated fisheries productivity (Igulu et al., 2013), as part of a wider matrix of well-connected adjacent ecosystems, they exert an undeniably desirable effect. Water pollution/sediment regulation, storm protection and fisheries habitat support etc, all depend on interactions between different marine ecosystems to varying degrees. For example, mangrove shelter provision function for juvenile fish species, may be more significant if nearby reefs act as reproductive habitats. The two ecosystems can thus be seen as an essential collaborative mechanism for successful completion of fisheries life cycles. By filtering pollutants in waste discharges, mangroves protect coastal communities as well as nearby coral reefs. Reefs, in turn, protect coasts by buffering oceanic waves and currents. Conservation efforts should thus ideally be extended to include all interconnected ecosystems, rather than being limited to solo mangroves.

3.3.3.2 Findings

In the current review, 80% of the captured articles allude to some positive influence of mangrove presence on fisheries yields (Figure 16). In Barbier et al., (2011) some varied evidence shows nursery and breeding habitat functions being more pronounced at the seaward fringe than the inland portions of mangrove ecosystems. Competent connectivity between marine ecosystems (e.g., mangroves, saltmarshes, seagrass meadows, reefs etc) is, however, essential for the nutrient and material fluxes that yield bumper fisheries. Furthermore, Blaber (2013) concluded that over a 10-year period, mangroves supplied protective functions that inured to the benefit of fisheries in estuaries. The abundance of more juvenile than adult fish in mangrove creeks further supports the nursery function of mangrove habitats according to Gadjzik et al., (2014). A call by Bell et al., (2018) for mangrove expansion as a climate change adaptive measure for dealing with food insecurity thus seems valid.

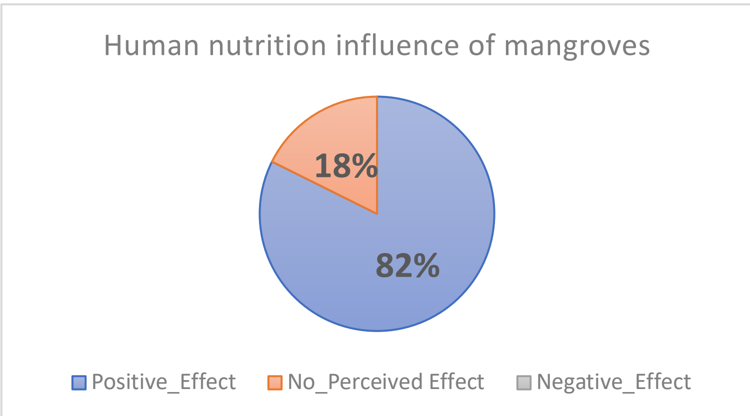

Figure 16: Reported nature of mangrove ecosystem impacts on nutrition exerted via food (mostly fisheries) support services.

Binh et al., (1997) and Rajendran and Kathiresan (1996) collectively showed how shrimp aquaculture productivity could experience between 30-50% productivity increase when associated with mangroves, leading to greater yields and economic returns. Furthermore, they demonstrate how shrimp farm effluents in turn promote mangrove plant growth due to their nutrient richness. Information on mangrove oysters, which serve as a valuable food source, suggests that mangroves facilitate the ideal conditions that promote oyster and oyster bed production. This is attributable primarily to the adaptation of juvenile forms of oysters (spat) to the tidal regimes of mangroves, which enables accelerated growth because of intermittent exposure to air (Kathiresan and Qasim, 2005). Results from Peng et al., (2013) show a 10% increase in aquaculture yield when a degraded mangrove site was replanted for the purpose. Mangrove litter reportedly contributed nearly 30% to the diet of the cultured fisheries, lending further credence to the findings of earlier studies by Binh et al., (1997) and Rajendran and Kathiresan, (1996).

Toxicity from environmental catastrophes such as oil spills engenders stunted growth and leaf deformities of plants, tree die-offs and associated impacts on various macrofauna within mangrove ecosystems (Lewis, 1979). Large scale lethalities and migrations within mussel, oyster and crab populations are reported in other older literature, in connection to disruptive oil spill events within mangrove ecosystems (Jernelöv et al., 1976; Garrity et al., 1994; Levings et al., 1994; Chan, 1977). A significant nutritional toll could be taken on the health of individuals who rely on these invertebrates for food. In Ngoile and Shunula (1992), local commercial fish species caught with movable traps in Zanzibar were found to be associated with mangrove vegetation, with certain species such as the rabbit fish *Siganus spp* being the most abundant. One mollusc (*Pyzarus spp*) was found only in the mangroves. Particularly for edible shellfish that are specially adapted to mangrove ecosystems alone, the resultant impacts of toxicities and catastrophic ecological disturbances could be grave for consumers.

Rahman et al (2018), Mandal et al (2012) and Primavera (1995) comment on mangrove support for grazing food chains, livestock, and honey production. The model presented by Mandal et al, who sought to explain the exact reason for overexploitation-related decline in fish populations, depict the role of mangroves in maintaining a balance between the detritus and grazing food chains. Additionally identified in this collection of research, is a linkage between a reduced water purification functions in degraded mangroves, and a decline in food crop production yields. In Primavera (1995), increased brackish water shrimp farming led to progressive mangrove loss, with concomitant deterioration of coastal water quality and domestic food crop decline. While fisheries, a contributor to human nutrition, was the benefit of highest value in the assessment by Rahman et al, honey production and fodder for livestock were the second and third most valued mangrove contributors to wellbeing along the Bangladeshi coast. Identification of the relevance of honey corresponds with the widely held knowledge about honeybees travelling long distances to forage in mangroves according to seasonal preferences (Krishnamurthy, 1990; Crane et al., 1993).

Indications from findings of this present review support the recognition by mangrove dwellers, of the importance of the ecosystem in safeguarding the livelihood and nutritional gains derived from fisheries (Walton et al., 2006; Rahman et al., 2018 in Table 5). Because of this belief, respondents in the study conducted by Martin et al., (2018) express willingness to relocate to mangrove areas as a coping strategy to address dwindling fisheries (Table 8).

Table 8: Human Nutrition Support Services of Mangrove Ecosystems

Authors	Description	Key Findings	Location
(Aburto-Oropeza et al., 2008)	To demonstrate the positive relationship between mangrove abundance at the water fringes, and fisheries landings	Mangrove-related fish and crabs account of up to 32% of small-scale fisheries landings. Destruction of mangroves has strong economic impacts on fishing communities and on food production in the region	Gulf of California
(Bell et al., 2018)	Exploration of adaptive strategies for maintaining food security in the face of climate change impacts on mangroves and seagrass habitats	Gap emerging between sustainable harvest practices and quantity of fish required for good nutrition. To optimise this gap, the landward expansion of mangrove communities and the maintenance of structural complexity of its associated fisheries habitats is suggested, among other strategies.	Pacific islands
(Blaber, 2013)	10-year review of fishes and fisheries in tropical estuarine environments	Neglected research issue of protective function that estuaries and mangroves provide for fisheries leads to expansion in popularity for restorative initiatives	Various
(Gajdzik et al., 2014)	Investigation of presumed nursery function of mangroves for ichthyofauna	Juvenile forms of food species more abundant in the mangrove creek than adults	East Africa (Kenya)

Authors	Description	Key Findings	Location
(Granek et al., 2009)	Examination of mangrove organic matter (OM) contribution to nutrient availability in coral reefs	Mangrove nutrient contribution decrease with increasing distance from the shore. Up to 57% of OM to sessile invertebrates, which play key roles in reef community structure, is supplied by mangroves	Panama
(Heithaus et al., 2011)	Examination of trophic structure within habitat types associated with fringe mangroves	No indication that mangrove productivity directly supports local fish populations	Western Australia
(Igulu et al., 2013)	Holistic exploration (modelling) of reliance of fish on mangroves as feeding habitat at multiple ecological levels	Two end-member mixing model showed 12-72% degree of fish reliance on mangrove food sources. High fisheries productivity of mangroves is supported by food sources from adjacent habitats, indicating that ecosystem connectivity is crucial	Global
(Jinks et al., 2020)	Sampling of species close to urbanisation to estimate trophic contribution of key primary producers to regional fisheries	Conservation of mangroves and phragmites would sustain fisheries production, as 6-70% of OM originate from wetland plants and underpin fisheries food webs	Eastern Australia
(Mandal et al., 2012)	Construction of holistic model of nutrient source to grazing to investigate cause of gradual decline in fish populations	Mangrove litter biomass plays key role in maintaining detritus and grazing food chains. Afforestation required to maintain ecological balance	West Bengal, India
(Martin et al., 2018)	To understand pressures faced by communities relocated due to environmental change	Climate change impacts identified as negatively affecting supply of marine and terrestrial foods. Relocation further inland and planting mangroves are preferred management/coping strategies	Yadua Island, Fiji
(Ngoile and Shunula, 1992)	Exploration of the status and exploitation of mangroves and associated fisheries	Mangrove wood utilised for charcoal, lime, and salt production. Fish species locally used as food were found to be bulk components of catches from water adjacent to mangroves. A particular mollusc species, used significantly as food and bait, was found only in mangroves.	Pemba Island, Zanzibar
(Peng et al., 2013)	Evaluation of combined aquaculture and mangrove replanting in a degraded mangrove site	Aquaculture ponds become self-purifying after mangrove replanting through mangrove nutrient uptake. Fisheries harvests 10% higher with replanted mangroves. Mangrove litterfall contributes up to 26% of cultured fish diet	South China
(Primavera, 1995)	Analysing effects of brackish water pond culture on mangroves	Loss of mangroves is most important consequence of brackish water pond culture, leading to pollution of coastal waters and domestic food crop decline	Philippines
(Shahraki et al., 2014)	Comparison of fish food webs in mangrove and non-mangrove habitats	Plankton and microphytobenthos sustain fisheries, regardless of habitat. Presence of mangroves was of minor importance	Persian Gulf
(Sheridan and Hays, 2003)	Assessment of mangrove role as nursery habitats via comparison of nekton quantities across alternate habitats	Direct consumption of mangrove detritus by nekton is minimal; prey abundance may be higher within mangroves. Roots and debris provide refuge from predation, promoting survival	Various
(Walton et al., 2006)	Assessment of direct benefits of a community-based mangrove restoration project	Over 90% of fishers identified mangroves as crucial fish nursery sites. Higher appreciation of benefits and 'willingness to pay' for protection by mangroves fishers	Philippines
(Rahman et al., 2018)	Economic valuation of the most important services from mangroves as perceived by ecosystem dependants	Fisheries provision had the highest value in terms of contributions to wellbeing, followed by honey provision and fodder for livestock, all contributors to human nutrition	Bangladesh

3.3.4 DISEASES, VECTORS AND MANGROVES

3.3.4.1 Background

Waters of bays and estuaries, where mangroves typically thrive, tend to naturally support, or receive microbial populations of both natural and anthropogenic waste origins. Grisi et al., (2010) demonstrate how pathogenic bacteria end up in the estuarine environment through discharges and land drainage. Alongside the presence of indigenous bacteria with pathogenic abilities, the microbial load of waste discharges into estuarine mangrove environments could pose significant public health concerns. Interestingly, as revealed by Penha-Lopes *et al*., (2011), monitoring and assessment of this risk is not prominent in the academic space.

Enteric pathogens like *E. coli*, *Vibrio spp* and *Salmonella spp*., agents of gastroenteric illness in humans, enter the aquatic environment via faecally contaminated domestic waste discharges. Within said settings, *E. Coli* compete with and knock out other microbes, thereby maximising their load and increasing the public health risk associated with consumption of food sourced therein (Gourmelon et al., 2006; Keller et al., 2013). Cholera-causing *Vibrio spp* occur naturally in estuarine/coastal ecosystems. Seafood harvested from coastal ecosystems can be sources of *Vibrio* contamination, which usually depends on the abundance of bacteria-enriching particulate organic matter (POM), and corresponds to aggravated risk of *Vibrio* illness (Grossart et al., 2005). Human salmonellosis, acquired through consumption of contaminated food and water, is also of importance when considering the mangrove ecosystem as an infectious disease reservoir. Schutze *et al*., (1999) suggested that sediments, water, and fauna in contaminated environments act as agents of *Salmonella* transmission. The prevalence of *Salmonella* in mangrove-sourced food species has been documented for food items including fish, crabs, and turtle meat (Grisi et al., 2010; Lotfy et al., 2011; Mealey et al., 2014).

Listeriosis, another human infection of substantial health consequence especially in pregnant women, is caused by *Listeria spp* of bacteria. Coastal waters are known to harbour strains of *Listeria*, particularly owing to their tolerance and preference for higher salt load and organic matter content, respectively. For this reason, studies have reported *Listeria* contamination of water, fish, sediments, and shellfish harvested from coastal ecosystems (Momtaz and Yadollahi, 2013; Bou-m'handi et al., 2007).

Overall, the ability of human pathogenic bacteria to survive in mangrove ecosystems is derived from tolerance of wide ranges of pH, salinity, turbidity, and other stress agents. The conditions of such ecosystems are in turn determined by the nature of natural, domestic, and industrial surface discharges, as well as consequences of nearby recreational activities (Alam and Zafar, 2013). The volumes of freshwater deposits, ocean currents and tidal action etc., all of which characterize the estuarine environment, regulate the nature of contaminant dispersal and bioaccumulation in the food chain.

Hundreds of insect species are associated with mangrove ecosystems, although most tend to be temporary residents, with lifecycles that stretch into other habitats (Ananda Rao et al., 1998). A number of these are of public health importance due to their roles as prolific vectors of human diseases. Although some of these vectors (e.g., mosquitoes and tsetse flies) can thrive in a range of habitats, their preference for wetland ecosystems is due to the aquatic-dependent aspects of their life cycles. Immature stages of mosquitoes for example, although prevalent in terrestrial environments, are better supported by aquatic and semi-aquatic ecosystems. For this reason, the disease risk posed by vector insects have been studied using a multidisciplinary approach that takes ecosystems and their ecological processes into account (Knight, 2011).

3.3.4.2 Findings

3.3.4.2.1 Pathogenic Microbes

Two papers captured in this review focused on microbes within mangrove-linked aquaculture ponds and on bivalves used as food sources (Gonzalez et al., 2011; and Ghaderpour et al., 2014) (Figure 17). Both arrived at similar conclusions, which highlight the risks to health of human consumers (Table 8). This negative health risk lies in the potential transmission of food-borne gastroenteritis, signalling an inability of mangrove ecosystems to mediate the impacts of coliform contamination.

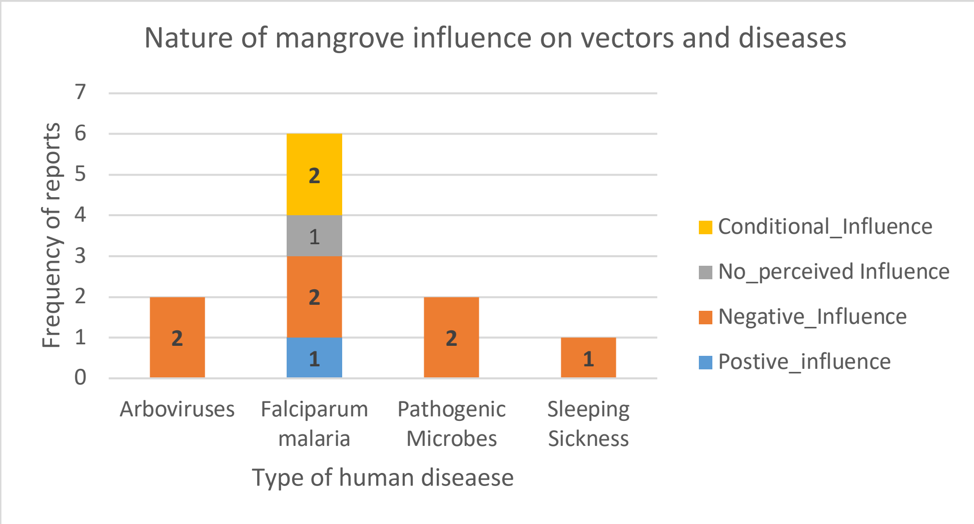

Figure 17: Nature of reported mangrove influence on disease and disease transmission agents (negative influence implies aggravation of disease risk)

3.3.4.2.2 Vector Organisms

Wetland management for human health benefits previously consisted of drainage to minimise mosquito proliferation (Horwitz and Finlayson, 2011). However, Thiere *et al.*, (2009) demonstrate how hitherto nuisance wetlands are now being recognised for their beneficial ecosystem services. It is therefore important to manage negative risks in ways that preserve these beneficial ecosystem services.

Crustacean burrows and tree holes (e.g., in *Avicennia spp.*) are ideal breeding locations for mosquitoes, which act as vectors of several vertebrate pathogens, and can occur in high numbers and diversity within mangal. The predatory action of larvivorous fish supplies a valuable biological control on mosquito oviposition. Therefore, fisheries supporting services of mangrove ecosystems tend to provide an indirect check on vector behaviour, that could deliver an additional public health benefit. This aligns with evidence from Ritchie and Laidlaw-Bell (1994), of lower populations of mosquitoes observed in mangrove ecosystems with high fish densities.

In this review, there was a diverse mix of motivations for studying vectors within mangrove ecosystems. Freiss (2016) presents a literature survey of colonial expedition accounts dating back to the 19th century, in which up to 60% of commentary discusses mangrove ecosystem disservices, especially the perception of mangrove forests as vector-borne disease reservoirs. Similar perceptions are thought to have fed into the legacy importance of mangroves for tropical peoples, who Carney (2017) suggests, have in the past used mangroves regions as refuge from foreigners who were less tolerant of the plasmodium malaria risks posed by the ecosystem.

Ten out of 11 articles allude to ecosystem disservices from mangroves in respect of vectors and agents of disease, with one study, (Jacups et al., 2012) failing to draw any clear perceivable relationship (See Figure 17 for breakdown). For the papers that reported a conditional influence, anthropogenic influences within the mangrove ecosystem were implicated. Ismail et al., (2018) emphasise how reduced mangrove disturbance leads to more predictable mosquito biting behaviour, presenting better opportunities for vector avoidance. It was however unclear how prevalence of diseases transmitted are affected by modulated vector biting behaviour. Carney (2017) points to the genetic human sickle cell-trait, as the condition that confers an advantage upon mangrove dwellers against mosquito-transmitted malaria. The lack of this trait leaves humans susceptible to the malaria threat that exists within tropical mangrove ecosystems.

Three studies (Jacups et al., 2012; Ismail et al., 2018; Claflin and Webb, 2017) that assessed the impacts of anthropogenic encroachment have shed light on how urban activities degrade wetlands and create the perfect environment for insect pests to proliferate. This does not seem to hold true for all parts of mangrove ecosystems though. As revealed by Dale et al., (2013) the impounding effects of mangroves could expose mosquito larvae and eggs, for example, to greater predation, while restricting oviposition at the same time, thereby controlling vector prevalence. Mosquitoes are the commonest vectors for some of the arboviruses for which mangroves serve as reservoirs. Bakau, haemorrhagic, dengue, Ketapang fevers among others, are spread by mangrove-dwelling mosquito species (Kathiresan and Bingham, 2001). Hoyos-Lopez et al., (2016) provided the sole update on the presence of arboviruses in coastal ecosystems in Colombia, including mangroves. Although vector behaviour and competence, with respect to the appraised mosquito-borne viruses (including yellow, dengue and West Nile fever), were not specifically investigated, the authors unveiled circulation patterns within mangroves that translate into possible human health risks.

Only one study (Courtin et al., 2010) focused on trypanosomiasis (sleeping sickness), concluding that human occupational activity close to mangroves increases transmission risk, due to the habitat support services mangroves provide for the tsetse fly vectors. The closer the mangrove frontier is to human activity, the higher the health risk from exposure to vector organisms (Table 9). In reducing this risk, drainage interventions have proven to be helpful in some instances, as reported by Jacups et al., (2012). Claflin and Webb (2017) further opine that following such interventions, circumstances may return to the pre-drainage conditions with time, provided the original intervention is meticulously planned and executed in a minimally ecologically disruptive manner. Otherwise, public health risks rise with human interference in mangrove ecosystems, leading to the erosion of public good will towards the wetland, in respect of proliferation of nuisance insects and diseases.

Table 9: Mangrove Ecosystems and Vectors/Agents of Human Disease

Disease/Vector	*Authors*	*Location*	*Focus of Analysis*	*Key Findings*
Falciparum Malaria/Various Mosquito Nuisance Impacts	(Carney, 2017)	Senegambia, West Africa, Brazilian coast	Overview of mangrove ecosystem use and significance in place-making as part of African and diasporan historical geography	The role of mangroves discussed within the context of sickle-cell-carrying trait in mangrove-dwelling Africans, which confers resistance to falciparum malaria risk posed by mangroves
	(Friess, 2016)	Various historical colonial locations	Quantification of historically discussed mangrove ecosystem services and disservices (1823-1883)	60% of commentary was on disservices, with mangroves especially considered to be disease reservoirs. Contemporary perceptions may have been moulded by such longstanding viewpoints
	(Claflin and Webb, 2017)	Parramatta River, Australia	Impact of land use within 500m of mangroves, on adult mosquito populations within the mangrove ecosystem	Urbanization degrades wetlands, enhances conditions for pest mosquitoes. Wetland rehabilitation could alleviate public health risks. Short-term, poorly planned interventions could increase mosquito populations and erode public good will
	(Dale et al., 2013)	Australia	Impact of saltmarsh encroachment on saltwater mosquito habitats, and mangrove displacement or replacement of these habitats	Mosquito larval habitats are complex, underpinned by topography and tidal interactions. Not all parts of mangrove ecosystem are suitable habitats. Greater impounding effect of mangroves would restrict oviposition and hatching while increasing fish predation

Disease/Vector	Authors	Location	Focus of Analysis	Key Findings
	(Jacups et al., 2012)	Darwin, Australia	Impact of drainage interventions on mosquito ecology and vegetation; and saltmarshes	Mosquito abundance declines in dry season; some species increase in the wet season. Non-target species disturbance is likely, but results indicate a near return to original drainage conditions
	(Ismail et al., 2018)	Malaysia	Day biting habits of mangrove mosquitoes in Kedah mangrove forests	Biting peaks during dawn and dusk for less disturbed areas but remained irregular throughout the day for others
Sleeping Sickness	(Courtin et al., 2010)	Forecariah, Guinea	Sleeping sickness transmission dynamics in mangrove areas to optimize control	Positive cases were associated with broader walking distances and occupation sites located within or close to mangroves.
Arboviruses	(Hoyos-Lopez et al., 2016)	Colombia	Effects of mangrove fragmentation, expansion of agricultural land use change etc on emerging and re-emerging arboviruses in coastal areas	Pathogenetic mosquito-borne arboviruses such as West Nile, Dengue, Yellow-fever etc indicates circulation patterns and possible human health risks in this zone. More data required to investigate vector competence and behaviour
	(Guzman-Teran et al., 2020)	Venezuela	Review of Alphavirus equine encephalitis virus	Strains of the virus continuously circulated in mangroves of Americas by mosquitoes and wild rodents, posing public health risk to nearby human settlements
Pathogenic Microbes	(Ghaderpour et al., 2014)	Malaysia	Faecal bacteria contamination in aquaculture and human settlement impacted mangrove estuary	Several types of bacteria pathogens, including coliforms, present with attendant human health risk
	(Gonzalez et al., 2011)	Venezuela	Microbiological quality of mangrove bivalves used as food	High food-borne illness risk from pathogens including *Clostridium spp*. and E. *coli* detected

3.4 SUMMARY AND CONCLUSIONS

Mangroves are useful to human society by virtue of their ecosystem diversity, which translates into the supply of a variety of beneficial goods and services. Some of these services, such as provision of medicines, pollution regulation and provisioning for food goods are health promoting. Conversely, some disservices to humanity also emanate from the otherwise positive habitat support function of mangrove ecosystems. Notable among these are the risks associated with pathogenic microbe transmission through human food chains. Further risks lie with parasitic and other disease agents like arboviruses through mangrove-dwelling vectors.

The medicinal value of mangroves resides in the bioactive metabolite richness of mangrove plants, endophytic fungi and associated actinobacteria. Aqueous and organic extracts of leaves, barks, stems, and roots of mangrove plants exhibit varying bioactive properties, which manifest in inhibitory action against pathogenic and food spoilage bacteria and fungi. Additional medicinal worth lies in the anti-inflammatory, antidiabetic, anticancer, antioxidant and antipyretic properties of extracts, which were reported in that decreasing order of abundance in the review literature. The most widely reported property is antibacterial activity, a particularly significant observation, given the current global antibiotic resistance conundrum currently confronting the pharmaceutical industry.

Regulation of sediment and aquatic chemistry is a function of mangrove ecosystems that delivers pollution control services to human communities. The evidence obtained in this review points to the fact that heavy and trace metal remediation, as well as attenuation of organic PCB and PAH pollutants, occurs in the mangrove environment. This function is demonstrated, in most instances, by the safe levels of toxic contaminants reported for mangrove ecosystem water and sediments despite pollution. The mediated bioaccumulation of otherwise harmful mineral and organic pollutants, through ecological interventions in the mangrove ecosystem, appears to deliver safe pollutant levels in mangrove goods such as fish and crustaceans. In some illustrations, some conditions exert limiting effects on optimal remediation benefits. These include contaminant load, ecological integrity, nature of anthropogenic alteration as well as magnitude of consumption of affected products.

The widely held belief that mangroves are vital for the provision of goods of human nutritional value seems to hold true for the substance of this review. Protective habitat support, reinforced by carbon and therefore organic matter richness characteristics, enables mangrove ecosystems to sustain breeding of edible vertebrate and invertebrate fauna, in a manner that fortifies and diversifies human food chains. 82% of the studies speak to detritus and nutrient shore up that support fisheries food chains, as well as provision of nursery and shelter functions for juvenile forms of fisheries. To a lesser extent, other nutritional benefits come in the form of honey production from mangrove-foraging honeybees, and provisioning services for grazing food chains. The acknowledgement of nutritional benefits of mangrove goods is sufficient to influence livelihood and nutrition choices of low-income mangrove dwellers. One shortfall in the literature considered, however, was the fact that there were not as many studies about Africa as there were about other tropical regions. Only one East African study (Kenya) was called up, highlighting a blind portion in the literature in terms of how the mangroves of other parts, such as West Africa, influence food supply and nutrition in surrounding settlements. Furthermore, studies focused on mangrove ecosystem impacts on production (e.g., quantity of fisheries). Little to nothing was reported in relation to nutritional quality (e.g., unique vitamin and mineral content of mangrove-supported food products). Bridging this gap in knowledge could reveal how mangrove influence on food options and alternatives available, helps humans meet specific nutritional needs.

Regarding threats posed to human health by a variety of harmful microbial constituents of waste discharges, there is little indication of competent mangrove mediation. Intervention is extended, in rare instances, to scenarios of infectious disease transmission, when ecological integrity facilitates natural vector and pathogen control mechanisms. However, the strength of the evidence of this nature is minimal. Because mangrove ecosystems provide suitable habitats for most food-borne pathogens, food goods from microbe-contaminated mangrove settings were shown to pose risks to human health. The aquatic mangrove environment, which maintains the life cycles of some nuisance insects and vectors, leads to abundance of vectors organisms, and a resultant prevalence of vector-borne diseases in mangrove populations. Except in situations where biological or anthropogenic interventive mechanisms are available to counteract this cocktail of disease entrenching effects, the combined outcomes lend credence to the infamous reputation of mangroves as far as human disease risk is concerned.

Only English language publications from the ISI 'Web of Science Database' have been included in this review, and the vast variety of measurement parameters in the records captured make a comparative, robust meta-analysis of findings unfeasible. Nonetheless, considering the health aspects of human wellbeing together, the evidence indicate that mangroves exert a more desirable than deleterious effect. For some of these links to human health, a greater consensus exists in the literature, whereas other evidence requires further targeted investigations. For example, with respect to impacts on infectious disease risk, while the studies report an undesirable outcome, a few suggest possibilities of more complex, non-linear link to mangroves. Not enough information is available to explain the conditional relationships that might exist between mangrove ecosystem processes and human disease outcomes. Especially, more investigations are required to clarify some of the theorised mix of consequences outlined in works like Duke *et. al*., (2014), and how they are influenced by changing states of ecosystems and social ecology.

Exploiting mangrove ecosystems for health-supporting benefits could obstruct functioning cycles that and affect the ability of the ecosystems to supply other services. Further insights into how to limit anthropogenic ecosystem stresses, could facilitate management strategies that enable these ecosystems to continue supplying crucial health-promoting ecosystem services, particularly in marginal communities. In pursuit of such insights, CHAPTER 4 of this thesis focuses on investigating how Ghana's mangroves have influenced health experiences over time. More expressly, the ways in which mangroves have been used, and how those interactions have evolved with ecosystem degradation and attempted restoration in mangrove communities, are considered. At the same time, the findings of the current chapter are compared to key-informant perspectives regarding how mangroves are linked with historical and current health experiences for communities found close to mangrove ecosystems. Thus, a broad framework of the extent to which the systematic review findings can be extrapolated to reflect the Ghanaian situation is constructed. This serves as a precursor to identifying the most relevant connections between mangroves and malaria, and thus opportunities for improved ecosystem and health management.

CHAPTER 4: THE CONTRIBUTIONS OF MANGROVES TO HUMAN HEALTH IN GHANA: INSIGHTS FROM A QUALITATIVE STUDY OF KEY INFORMANTS

4.1 INTRODUCTION

4.1.1 Background

A considerable proportion of the world's population lives within 100km of coastal areas, which harbour critical terrestrial, marine and hybrid ecosystems such as mangroves (Hoegh-Guldberg, 2015). The nutritional, livelihood and cultural identity needs of nearly 57 million people in 123 countries worldwide depend on the continued supply of marine and coastal ecosystem services (MCES) (Griffin et al., 2019). Mangroves are highly productive, typically tropical riverine and coastal forest ecosystems, comprising of specialised forms of vegetation that thrive in a variety of water depths and salinity, and have specially adapted roots for 'breathing' under anoxic conditions. Apart from the substantial contributions made to local economies, these unique providers of MCES serve as habitats for a wide range of biodiversity, and supply other vital provisioning (e.g., fisheries support), cultural and regulating ecosystem services (MA, 2005). Biodiversity, habitat, and ecological disruptions driven by anthropogenic and natural phenomena continue to catalyse mangrove loss, with attendant decreases in supply of associated MCES. Climate Change impacts and unsustainable development activities are expected to speed up this negative trend. The Millennium Ecosystem Assessment (2005) reports that a third of the world's mangroves have been lost at a rate that is estimated by Duke *et al*., (2014) to be 5 times the average rate of forest loss experienced globally.

Policies that protect and improve biodiversity and ecological conditions in crucial ecosystems in a manner that safeguards both economic prosperity and human wellbeing are increasing in popularity. The Sustainable Development Goals of the United Nations, instituted in 2015, provide an international development scaffold which puts nature conservation and human wellbeing in focus (UNGA, 2015). Conceptual frameworks have been developed by scholars to help understand and quantify ecosystem service impacts on human wellbeing (Yang et al., 2015; Milner-Gulland et al., 2014), and health as an aspect of wellbeing, has not been excluded from these efforts.

Unsustainable trajectories of resource consumption, ecosystem degradation and environmental change have been cited as potentially capable of overturning public health gains, especially in the most vulnerable societies (Whitmee et al., 2015). Most recently, the emergence of the pandemic-causing covid-19 virus has piqued concerns about how disease outbreak risk factors are affected by damages to ecosystem integrity (Evans et al., 2020). Unfortunately, some of the evidence required to incentivise policy formulation and reform is subjective, fragmented across disciplines and skewed towards socio-economic outcomes. In instances where conservation has been deemed necessary, evidence on the human health impacts of various interventions is limited for forest, marine and freshwater ecosystems, as compared to other wellbeing aspects (McKinnon et al., 2016).

To identify, monitor and evaluate what constitutes relevant progress towards meeting wellbeing targets of sustainable development, there is a need for better evidence, especially at more discrete spatial levels (Lu et al., 2015). Seeking qualitative evidence of this nature, this study aims to bridge an important knowledge gap with respect to the most significant impacts of mangrove ecosystems on local human health, as an aspect of wellbeing. To this end, information drawn from experiences of key informants regarding mangrove-human health relationships in coastal communities in Ghana is explored and compiled. The central output is a synthesis of the health impacts of human interaction with mangroves from the Ghanaian perspective, and how this has evolved with time and socio-ecological interventions. This new knowledge highlights the degree to which lessons from health-related aspects of human-mangrove interactions reported elsewhere, could be applied meaningfully to the Ghanaian setting, and vice-versa. The findings could facilitate rapid location of practical evidence for guiding the most suitable conservation and public health policy interventions in similar localities.

4.1.2 Research Objectives and Questions

This study is a qualitative inquiry into the relationships between mangroves and human health experiences in Ghana, based on interpretations that can be drawn from the views espoused by key informants. The specific study objectives are as follows:

- A sampling of perceptions about the past and present states and socio-economic significance of mangrove ecosystems in Ghana
- An exploration of the nature of human-mangrove interactions in Ghana and, resultant effects on community health experiences
- To determine observed and potential ways in which ecosystem interventions influence mangrove-human health outcomes.
- An investigation into the role of formal public health interventions in modulating mangrove-related health experiences and outcomes

To accomplish the objectives listed above, this study uses semi-structured interviews designed to elicit the most relevant data from respondents that answer these main research questions:

RQv. What are some of the past, present, and potential future characteristics of mangroves and their use in Ghana?

RQvi. How does human-mangrove interaction affect human health, and what differences do ecosystem interventions make?

RQvii. Are there adequate alternatives for meeting the health needs otherwise supplied via human-mangrove interactions?

4.1.3 Case Context

Mangrove land cover in Ghana was estimated by Agyeman et al (2007) to be about 112km^2, mostly occurring along lagoons and estuaries of the 550km^2 coastal belt, and the south-western wet evergreen zones. These ecosystems are sparsely distributed, varying in foliage maturity and density. Although the species diversity of true mangrove vegetation in the country is limited (Wilkie and Fortuna, 2003), a wide range of associated flora and fauna can be found within Ghana's mangroves, many of which are of economic, wellbeing and cultural significance in neighbouring communities (Ntyam, 2014; Macintosh and Ashton, 2003). Mangroves have long been regarded as vital sources of wood for diverse uses, water pollution mediators, key habitats for many rare species, shoreline protectors and providers of essential food goods (Ayisi and Addo, 1994; UNEP, 2006; Bentum et al., 2011; Ntiamoa-Baidu and Gordon, 1991).

Ghana's mangrove forests, sharing the fate of others like them in the Gulf of Guinea, have faced a steady decline in cover and ecosystem health due to a combination of threats. The lack of robust legal frameworks and protective land tenure systems, along with habitat destruction, mangrove resource exploitation and land use change are some of the main drivers of mangrove degradation in the country (Kumi et al., 2015; Asante et al., 2017; FAO, 2010). With the economic pressures that favour mangrove loss projected to intensify in pursuit of development goals, it is unlikely that mangrove decline would be naturally halted or reversed. This translates to a concomitant curtailment of the economic, social and wellbeing benefits of mangrove ecosystem services, unless the appropriate interventions are made to safeguard same.

Some indigenous strategies exist for mangrove conservation, including prohibitions and taboos which, in tandem with community based and externally driven revegetation and ecological restoration initiatives, have had positive effects on mangrove ecosystem preservation in the country (Koranteng et al., 2000; Ntiamoa-Baidu, 1991; Aheto et al., 2016; Asante et al., 2017). These regimes are often consequential to the long-standing recognition of the socio-economic benefits of human-mangrove interactions, especially in the poorest communities where freedom of choice is limited. Although complete reversal of ecosystem degradation is unrealistic given available ecological evidence (Macintosh and Ashton, 2002), there is yet enough validation of the return of valuable benefits following ecosystem restoration (Binh et al., 1997). This suggests that human wellbeing benefits from mangrove-protective policy interventions, provided sufficient confirmation of vital relationships with aspects of wellbeing can be established. Human health is one such crucial aspect of wellbeing, which is yet to be investigated with respect to mangroves and Ghana.

Compared to other sub-Saharan African countries, Ghana exhibits reasonable formal health sector outcomes. Funding shortfalls in the supply and delivery of public health goods and services are often augmented with international donor support (Saleh, 2013). Despite having made major strides in its universal health coverage over time, from 29.5% in the 1990s to 49% in 2019 (Lozano et al., 2020), access remains lopsided, to the extent that inequities persist in availability of health facilities and human resources (Zakariah et al., 2014; Saleh, 2012). A recent 'Global Burden of Disease' assessment indicates that communicable, maternal, neonatal, and nutritional diseases are the leading causes of death; with ailments such as malaria, tuberculosis, diarrheal diseases, lower respiratory tract infections and diabetes leading the charts in this regard (Vos et al., 2020). According to Escribano-Ferrer (2016) and the Ghana Statistical Service (2011), high mortality rates in under-fives and expectant mothers, low health insurance coverage for primary ailments, non-adherence to diagnosis, treatment, and professional protocols etc all remain more prevalent in populations of poorer households and communities. This trend indicates that the poorest Ghanaians have limited access to the best quality of care via the formally instituted public healthcare delivery route. For this group of people, availability of alternative health protection and care options thus remains valuable.

There are instances where alternative health security implies reliance on nature-dependent traditional remedies that are based on indigenous knowledge (Ahorlu, 2005). In other situations, redemption comes in the form of reduction in the major health-related environmental risk factors (Prüss-Ustün et al., 2014; Boadi, 2004) which are often delivered through ecological mediation of sanitation, pollution, and disease vector abundance/behaviour etc. Good nutrition, yet another key determinant in the quest for better health, is boosted by the continued supply of nourishing food and potable water (Boon, 2019; Mockenhaupt et al., 2004), which are incidentally products of provisioning services of specialised natural ecosystems like freshwater and mangroves. This study seeks to ascertain the Ghanaian perspective on how the presence, use and restoration of mangrove resources mutually affect states of health in contiguous communities.

4.2 METHODS

4.2.1 Study Design

Through the interpretation of viewpoints expressed by key informants, this study explores the ways in which mangrove ecosystems influence health outcomes experienced in nearby human communities in line with guidelines found in Hay (2000). The choice of methodology was predicated on several reflections. The general approach was to gather rich country-specific information that identifies locally unique patterns and themes regarding this phenomenon (Creswell and Poth, 2016). The need to gather data efficiently and effectively, given the limited amount of time and resources available, was another key consideration (Lincoln and Guba, 1985). Moreover, the flexible method of semi-structured key informant interviews, which makes room for open-ended and iterative questions, was chosen to satisfy the open and exploratory nature of the research questions.

Marshall, (1996) describes some disadvantages of this approach, such as informant inclination to disclose only information they deem to be socially and politically acceptable. Secondly, inadvertent selection of people seeking status improvement in a society but who may not necessarily be knowledgeable is also possible. These two biases were minimised as much as possible by carefully selecting respondents from a variety of social groups, of diverse political and social backgrounds and with varying interests and expertise. Guaranteed anonymity provided an extra layer of confidence as impetus for participants to be less constrained in their assessments and responses.

The research was approved by the Faculty of Science and Technology Research Ethics Committee (FSTREC) of Lancaster University. The contents of a consent form were verbally and electronically presented to the participants, and on each occasion, the interactive process was only initiated following informed consent from the respondent.

4.2.2 Participant Selection and Description

Data collection for this exercise consisted of conducting semi-structured interviews with respondents of stakeholder groups deemed to be potential sources of rich insights and ideas on mangroves and potential links to human health in Ghana. A snowballing-supported purposive sampling strategy was thus adopted, according to researcher judgment and the purpose of research (Babbie, 1995). Although provision was made for a supplementary opportunistic sampling, no notable or unpredicted leads were encountered during the interview process that warranted same. One potential interviewee recommendation was pursued, but ultimately abandoned due to participant unavailability.

A balance of participants with different circumstances, knowledge and experience was prioritised. This balance was achieved through the recruitment and selection process, by ensuring broad spectrum representation of backgrounds and interests across gender, age, depth, and nature of experience. Informants with a wide range of views were selected from stakeholder groups which were deemed to be appropriate, based on positions in society, expertise, and skills relative to the research phenomenon (Kruger and Stones, 1981). Particular attention was given to groups of people with significant interests in mangroves and public health issues, in a way that affords them the unique opportunities to observe behaviours and trends, as well us to infer useful information from prevailing culture. Because the assessment was based on norms within mangrove societies, individuals who have achieved influential statuses and positions of responsibility in the Ghanaian community, and who were most likely to be familiar with its norms, were considered. It was anticipated that such respondents would be most knowledgeable of, and conformant to the norms of interest, with all relevant biases noted. Information on the duration of the respondent exposure to the knowledge and/or experiences of interest was also gathered in each instance (Table 10)

After careful reflection on the above purposive sampling criteria, Individuals from the academic, health management, media, nature conservation and NGO sectors were considered. Residents of mangrove communities were also included to capture lived experiences. Invitations were made to the participants or their representatives (as the case may be) first via email, followed by scheduling of interviews via telephone. Actual interview sessions lasted an average of between 40 to 50 minutes and were conducted remotely in English using telephone or VOIP (Voice over internet protocol).

4.2.3 Data Collection Process

Using evidence from a systematic literature review of mangrove links to human health as a basis (See 0), an interview guide was prepared and adapted for each session, taking experiences from previous interviews as well as the nature and depth of informant knowledge into consideration. A decision tree was included, which gave options for non-applicable questions to be skipped. There were five categories of open-ended questions as follows:

A. Introduction: Respondent profile and nature of expertise
B. Nature of mangroves in Ghana (threats, land coverage, governance and use, revegetation/conservation)
C. Nature of mangrove-human interactions
D. Public health interventions in mangrove communities
E. Links between states of mangroves, mangrove use and health.

The participants were not prevented from commenting beyond the main questions asked, and researcher intervention was instigated only for the purposes of clarification and introduction of new questions and themes. Such interventions consisted of additional follow-up or confirmatory questions and requests for clear examples. All interviews were audiotaped with informant consent, and handwritten notes about researcher observations were also recorded in a journal. Digital audio recordings of interviews were then fully transcribed for subsequent coding and interpretation using NVIVO software, alongside the thoughts captured in the researcher notes, after which the primary files were destroyed.

4.2.4 Analytic Framework

Based on the findings of a systematic review on mangrove links to key human health aspects (0), the conceptual framework in Figure 18 served as a basis for the selection of the key informants, for formulation of the interview questions and for data analysis. The pressures that mangroves face, apart from environmental change, include being used unsustainably for livelihood activities and for non-livelihood provisioning, cultural and supporting services. The goods and services involved in these interactions include those that directly or indirectly have health consequences. Impacts of dams and climate change are the other threats mangroves face. These phenomena together can lead to mangrove degradation and attendant consequences, including decline in multiple ecosystem services, some of which affect health of human populations. These undesirable conditions then give rise to concerns in neighbouring communities, pique researcher interest and necessitate remedial policy formulation or revision at the local and central government level. In some instances, the collective result is for healthcare, mangrove restoration and conservation initiatives to arise from community, national or NGO efforts, leading to a potential reversal or curtailment of any health effects of ecosystem degradation. Alternatively, lack of interventions in degraded mangroves would result either in the persistence of health consequences, or in the pursuit of substitute non-mangrove-related health solutions.

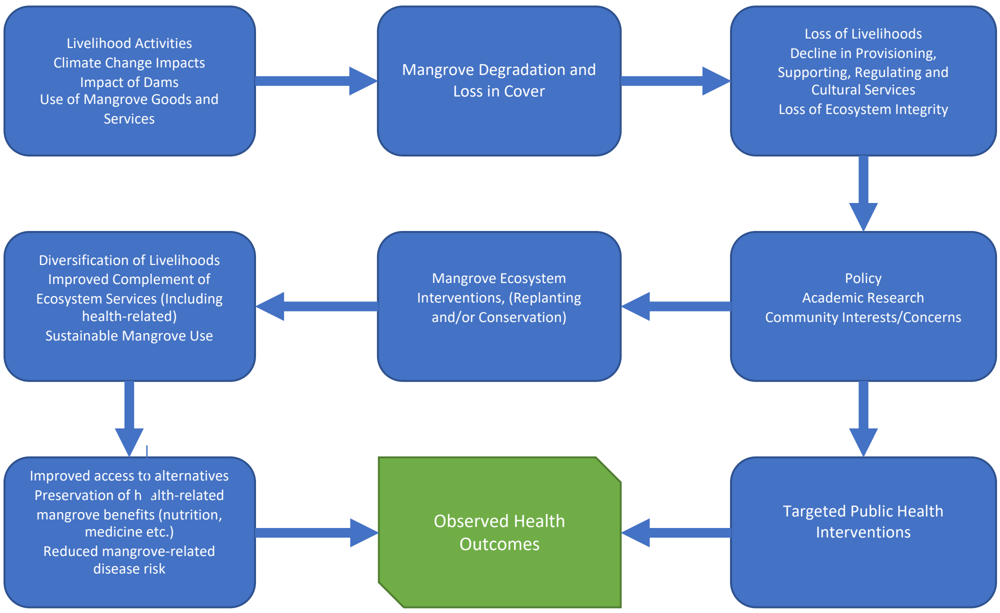

Figure 18: Conceptual Framework of Potential Influences of Mangrove Use and Intervention Patterns on Health Outcomes

4.3 RESULTS AND DISCUSSION

Data from 14 key informant interviews, made up of responses from 5 female and 9 male participants, were analysed in this study. The following are the three main anchor themes around which the questions were framed:

- Historical mangrove access, use and dependence dynamics among residents.
- Changes in health consequences of mangrove use with time.
- The differences that mangrove degradation and interventions (public health, ecosystem) make on mangrove-related health consequences observed today.

The results are therefore discussed within these three main contexts which directly address the research questions.

Participants brought a wide range of expertise to bear, varying from conservation and ecological restoration experience, through academic and research knowledge to health policy implementation (Table 10). The viewpoints expressed by media professionals were limited, with their specialised environmental knowledge being skewed more towards waste management and sanitation dimensions of the topic.

Table 10: Characteristics of Interview Participants

Participant ID and Sector	Sex (Male-M; Female-F)	Education Level	Occupation/Role	Area(s) of expertise	Duration of Expertise (years)
Academia (A1)	M	Tertiary	University Staff	Ecosystems and conservation research, Policy Advice	>25
Academia (A2)	M	Tertiary	University Staff	Ecosystems and conservation research, Policy Advice	10-15
Conservation (C1)	M	Tertiary	Wetland Manager	Wildlife and ecosystems protection, policy implementation, climate change, advocacy	15-20
Conservation (C2)	M	Tertiary	Wetland Manager	Wildlife and ecosystems protection, policy implementation, climate change, advocacy	20-25
Media (J1)	F	Tertiary	Environmental Journalist	Ecosystem services, wildlife protection and sanitation reporting	5-10
Media (J2)	M	Tertiary	Environmental Journalist	Ecosystem services, wildlife protection and climate change reporting	15-20
Conservation NGO (N1)	M	Tertiary	Executive Director	Wildlife protection, conservation, and climate change project management/advocacy	15
Public Health NGO (N2)	M	Tertiary	Project Officer	Public health project management and advocacy	5-10
Health Administrator (H1)	F	Tertiary	District Director	Public health Policy Implementation, monitoring, and research	10
Health Administration (H2)	F	Tertiary	District Director	Public health Policy Implementation, monitoring, and research	5-10
Health Administration (H3)	M	Tertiary	Health information Officer	Public health data management and research	10-15
Residence (R1)	F	Primary	Fish seller (Anyanui)	Local resident	>25
Residence (R2)	F	Primary	Farmer (Tunu)	Local resident	15-20
Residence (R3)	M	Secondary	Mason (Obane)	Local resident	15-20

4.3.1 THE HUMAN-MANGROVE NEXUS HAS EVOLVED IN GHANA (RQv)

4.3.1.1 Mangrove Characteristics

Mangroves were identified and described by participants as the unique salt-tolerant plants that grow on the fringes of the coast along estuaries, lagoons, and rivers. In a few instances, inland mangroves were also mentioned, but people would first associate mangroves with coastal aquatic environments. The Volta estuary mangroves, found along the eastern coast of the country (Figure 19), were regarded by interviewees as the most extensive mangrove stretch in the country, both in terms of vegetation density, and geographical expanse. Respondents with in-depth academic knowledge proffered perspectives on the ecological characteristics of mangrove ecosystems, including insights into the unique biodiversity contained therein. However, benefits accrued to human settlements because of mangrove ecosystems were more readily acknowledged. Significant amongst these were the provisioning services of wood production and fisheries support, the regulatory services of erosion control and shoreline protection, as well as various cultural and recreational benefits (Table 11). Habitat provision was noted as a particularly important benefit, not least because some endangered and rare species of fauna inhabit Ghana's mangrove ecosystems. Some of the species are permanent residents, such as the African Python, *Python sebae* and the monitor lizard *Varanus bitatawa*, while others are seasonal visitors including terns (*Sterna spp.*).

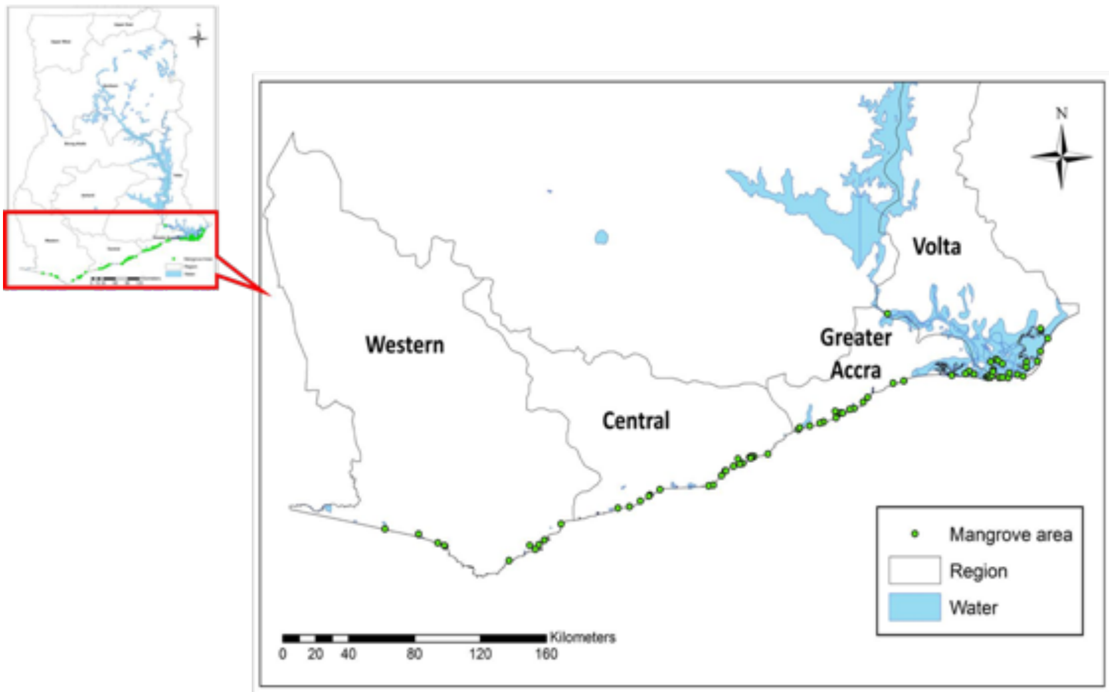

Figure 19: Outline of Mangrove Distribution Along the Coast of Ghana (Nunoo and Agyekumhene, 2014)

Table 11: Summary of ecosystem goods and Services Identified by respondents.

Provisioning Services	Supporting Services	Regulating Services	Cultural Services	Health -Related Services
• Firewood • Wood for charcoal • Poles (construction) • Poles (brush park fish farming) • Traditional medicines	• Habitats for fisheries • Soil formation • Habitats for non-aquatic biodiversity (migratory birds, insects, reptiles, molluscs etc)	• Coastal (storm) protection • Pollutant trapping (solid waste)	• Recreational beauty • Ecotourism • Spiritual/religious beliefs • Ecological research	• Traditional medicines • Habitats for fisheries • Ecological research • Habitats for non-aquatic biodiversity • Pollutant trapping

4.3.1.2 Use and Governance Patterns vs Effects.

According to the interviewees, mangrove lands are owned by individuals, families, small co-operative groups, and occasionally, traditional councils and government agencies (notably the Forestry Commission). Access to mangrove lands is usually restricted to members of such groups, with the exception being those acquired by the government for conservation purposes in line with the requirements of the Ramsar Convention. Financial compensation is usually paid to affected families for the areas earmarked for restoration, conservation, or protection by government agencies, although some degree of regulated access is allowed in some instances. These comments from two interviewees with conservation experience illustrate the different governance approaches observed in the Ghanaian setting.

> *"Well, sometimes they restrict use by telling you which mangroves belong to specific families, and strangers are strictly prevented for having rights to those mangroves. So those rules and regulations protect the mangroves. Only those families can cut them, and they have ways of monitoring the growth".*

> *"There are also areas where the government pays compensation to the families. For example, in the Sakumo lagoon area, the government has paid compensation to families. That makes the land area the property of the government, in which case they are ideally not supposed to harvest trees, although some variations exist".*

At the Obane restored mangrove project site for example, although tree cutting is prohibited by locally agreed by-laws, residents are allowed to collect naturally shed wood pieces, as well as crabs, snails and other goods found within the mangrove environment. In the absence of extensive legislation specifically targeted at mangroves in Ghana, there is a shared responsibility for stakeholders; established both organically due to local taboos and prohibitions, and more intentionally under a 'National Wetlands Conservation Strategy' (Nunoo and Agyekumhene, 2014). The Ramsar site designation conferred on five coastal wetlands, some of which harbour mangroves, provides an additional regulatory incentive for the protective management of mangrove resources under the 'wise use' principle (Ramsar, 2014b). Further, a National Land Policy and the Environmental Impact Assessment Regulation of 1999 have a combined focus of stipulating best practice measures for the judicious use of land and their integral resources, with desirable repercussions for mangrove protection. For example, these comments from three participants further demonstrate the nature of the mix of existing protective regimes related to mangrove lands.

> *"Some communities have taboos, in the form of restricted days when people are not allowed to go to the mangroves to harvest wood or fish etc. but I don't have any specific knowledge in relation to that".*

> *"Often it is not that they are intentionally protecting the trees, but they are worshipping the water bodies as vessels for deities, and by extension the mangroves. So those are the main types of taboos, myths, superstitions, and traditional systems in place to protect mangroves".*

> *"I would not say I know much about land tenure for those areas, but for those areas designated as Ramsar sites, I can say Government has some public rights to those areas. But when it comes to other types, I do not think they would be any different for current land tenure arrangements in place for other types of lands in the country".*

All but one respondent acknowledged that mangrove land cover has diminished, both at the local and national level. According to the single dissenting perspective, mangrove cover has increased in some areas where regulatory frameworks have been applied as part of ecological restoration instituted to mitigate previous decline in cover. One such location was the Obane community, which is home to a restored mangrove project.

There is a consensus that such restoration projects have helped to preserve the trees, protect biodiversity, and create awareness about the threats that ought to be curtailed. Vegetation and ecological restoration projects are usually funded by foreign/ external donors and come with added livelihood enhancement programs to help reduce the economic pressures that fuel mangrove degradation. Such projects are maximally effective for as long as there is funding available, and without by-laws to protect replanted forests, the risk of future return to tree harvesting often lingers. Thus, the progression of degradation by inference hinges on the availability of alternative livelihoods, access to the land and the existence of conservation regulations, all of which had different outlooks in the past compared to today. One respondent with vast experience in planning, implementation and monitoring of mangrove restoration projects had this to say:

> *"We had a lot of NGOs going into mangrove restoration, so around 2013, an increase in the coverage of mangroves along the coast of Ghana was observed. But most projects are driven by funding, so typically as soon as the funding dwindles or stops, the projects, if they do not have strong sustainability components, begin to fizzle. After that period, mangrove coverage started declining".*

The failure of residents to extend conversations on local practices to mangrove ecological processes suggests a lack of knowledge or interest in what these processes involve, and how they relate to the ecosystem goods and services they enjoy. This limitation in indigenous awareness provides some insights into why unsustainable tree harvesting and land conversion issues remained unattended for a long time, leading to complete mangrove loss in some areas. In communities like Anyanui and others in the Volta Region, where sale of mangrove wood is a major income earner, locally initiated revegetation of cleared woodland is an established practice. Trees are allowed to grow for at least 5 years before being harvested, a replacement cultivation culture borne out of the recognition of the importance of mangrove survival to local economies. As one participant explained:

“However, the largest expanse is found in the Volta Region, and that is also because the people in the Volta, especially in the Anyanui area, farm mangroves as a livelihood. They plant the mangroves, nurture it to maturity and then they harvest to sell after some 5 or so years”.

This five-year rotation tenure seems to align with general flowering age for juvenile mangroves, either intentionally or by chance, but can still be upgraded to more long-term and comprehensive regimes that make room for mangrove to fully mature and reproduce before being harvested. As more mature forests are thought to supply greater magnitudes and varieties of ecosystem goods and services (Hogarth, 2015; Walton et al., 2006), giving the forest and ecosystem the time to become fully established would be more economically desirable than otherwise, and thus deliver greater wellbeing returns.

Comments from interviewees about other communities where the link with livelihood is not as important, point to a lack of robust ecosystem management systems, whereby people often resort to other available livelihood pursuits when mangrove health declines. Externally instigated and managed sensitization and restoration programmes thus become imperative in such communities. Those programmes have contributed to the heightened awareness about the ecological importance of mangroves observed today. This comment made by a conservation expert emphasizes the significance of stakeholder engagement in respect of the design of restoration initiatives to suit such communities.

“I can speak for the communities where we have had restoration projects. We go to the community, talking to them, trying to foster the relationship with all the stakeholders so that they can agree that this resource is important and needs protection and that we need them to facilitate it for us. We offer start-up capital, especially to women. We have a management committee for the Ramsar site, and the officer is also a member of the committee. The idea is that we know successful conservation projects can be linked to alternative livelihoods”.

As previously mentioned, one notable example of restoration is the Obane project in the Greater Accra Region, undertaken by the Wildlife Division of the Forestry Commission, with assistance from the UNDP-GEF. This project included some directives that ensure more sustainable stakeholder use of the mangroves to ensure maximised benefits for all interests. If the land ownership regimes are altered in any way to facilitate mangrove wetland protection, then the rights that people have to mangrove goods and services are weakened. People who traditionally would have had unfettered access to mangrove lands due to familial or other group ties, could be restricted by conservation regimes instituted by mangrove restoration experts. This consequently transforms the way local lives and wellbeing are impacted by the mangroves nearby, as compared to times in the past. While revegetation catalyses a return of ecosystem goods and services, such projects if accompanied by curtailment of access, limit the magnitude of goods that people can enjoy in the aftermath. However, heightened preservation awareness and attendant regulatory systems work in tandem help to guarantee more sustainable use, and hence an extension of benefits over spatiotemporal scales. Figure 20 summarises the interplay of resource use factors that influence mangrove degradation in Ghana.

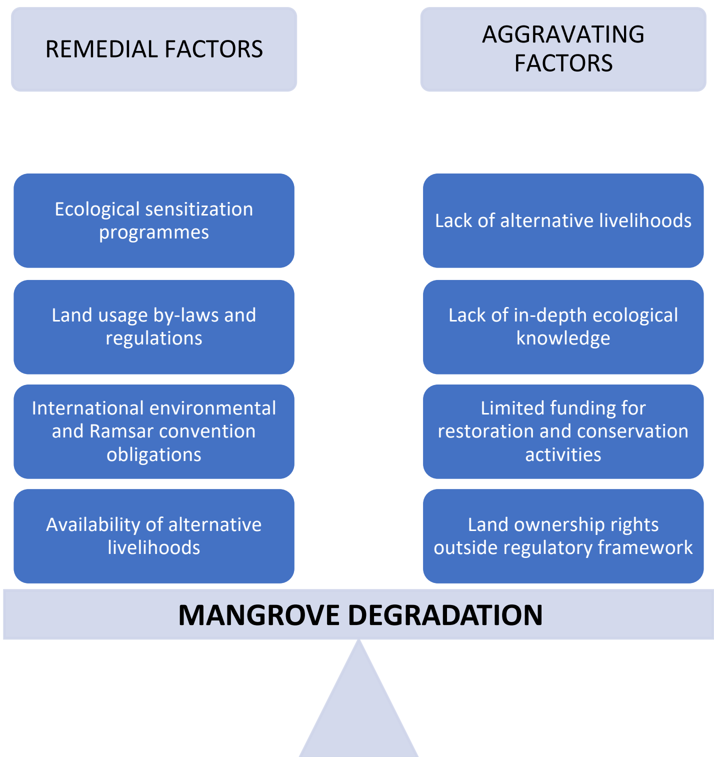

Figure 20: Summary of mangrove use characteristics and how they influence ecosystem degradation. Increasing 'aggravating factors' exacerbate ecosystem degradation, while 'remedial factors' help to restore ecological balance.

4.3.1.3 Key Threats

Natural and anthropogenic mangrove degradative activities can alter the structural complexity of the ecosystem, leading to disruptions in ecological processes which directly and indirectly impact ecosystem services and goods. Conversely, elimination of degradative ecosystem stressors would stimulate an ecological recovery pathway which facilitates a more pronounced and sustained delivery of related goods and services (Bosire et al., 2008; Walton et al., 2007; Walton et al., 2006). Against this knowledge, interviewees were asked about the circumstances and practices that place mangrove ecosystem integrity in jeopardy, to interrogate how such disruptions could potentially curtail the observed health benefits of mangroves.

Considering all catalogued commentaries, the wetland locations with the most extensive degree of degradation appear to be the Densu Delta and Sakumo wetlands in the Greater Accra Region. Conservation experts attest to this situation, ascribing the poor state of these mangrove wetlands to extensive urban encroachment, the effects of which continue to erode the gains of conservation efforts. As one participant commented:

> *"Unfortunately, Sakumo and Densu Ramsar sites are not pleasant areas to talk about because the urbanisation has almost encroached upon and taken over the entire site".*

According to the interviewees, the key threat to mangrove survival is overharvesting of the trees, which is widespread due to the numerous economic benefits of mangrove wood. Apart from use as fuelwood (sometimes through charcoal production) for cooking, and for fish smoking, a few other desirable uses for mangrove wood were highlighted. These included use as aggregation devices for aquaculture and as construction materials. Related responses from two participants are captured as follows:

> *"Overharvesting is the major cause of mangrove depletion along the coast of Ghana. This is due to use for charcoal production, brush park farming and fish smoking, as there is a belief that if you smoke fish with mangrove (wood) it*

tastes better. The second threat we found was land conversion, people destroying mangrove land for aquaculture and shrimp farming. Sometimes people even convert mangrove areas into salt pans".

"Bamboos and other wood which grow together in the mangrove ecosystem are felled wantonly for construction and for furniture, while the swamps are filled with earth in order to construct a building on that land".

Mangrove land conversion was the other key threat recognised by participants, and sometimes this was mentioned within the context of ecosystem degradation. Land conversion activities could have benefits that improve income levels, creating the financial empowerment to afford a wider range of well-being guarantees, including those related to health. The drivers behind such strategies include demand for real estate, small scale agriculture, aquaculture (oyster/shrimp production), salt mining and brush park fish farming pressures. For example, a conservation NGO executive provided this viewpoint about mangrove land conversion:

"I can mention land conversion. If you go to areas in the Central Region, around the Muni-Pomadze Ramsar site, you see a lot of these mangrove habitats being converted for other purposes such as agriculture, salt pans, real estate development etc. These are the emerging threats".

Reduced freshwater inflows, which hamper propagule dispersal, were also recognised as a major problem. Damming of the Volta River for example, was cited as a factor in mangrove decline particularly in the Volta estuary area, as illustrated in this comment:

"The construction of the Akosombo dam has drastically reduced the in-flow of the brackish water to the mangrove habitats in the Volta estuary, so their geographical coverage has significantly reduced. The natural regeneration was rendered ineffective because there was not enough water getting to the area to inundate it and make it suitable enough for the mangroves to regenerate".

Two dams were constructed along the length of the Volta River by the Volta River Authority for the purpose of generating hydroelectricity, followed by a recent third, leading to a significant reduction in downstream volume and flow. These developments account for up to 80% of the electricity needs of Ghana, forming an indispensable backbone and catalyst of beneficial economic activity. The ecological consequences have however been detrimental, one of which is that reduced freshwater inflows now hamper mangrove regeneration potential by stifling effective propagule dispersal. In such situations the impacts of overharvesting and habitat destruction are amplified, as fewer new trees naturally grow to replace those harvested or lost. While some local indigenous knowledge about manual mangrove cultivation survives, the popularity and application of this expertise is spatially skewed and seems to be fading with mounting livelihood diversification and rural-urban migration. As one participant observed:

> *"Sometimes they try to plant more but it is not so easy. I think maybe us the younger generation are not so skilled at those things like the older ones because they do not have plans of staying here all their lives. But there are those people in the islands like Bomigo, they know how to manage mangroves well, because the trees have always been part of their daily lives"?*

Table 12 summarises how frequently the various activities perceived as threats to mangroves in Ghana were cited by interviewees.

Table 12: Summary of Activities Cited as Threatening to Mangroves in Ghana

Activity	Citation Frequency
Overharvesting of mangrove wood **(Charcoal production, fuelwood, construction input, brush park sticks, furniture, fish smoking)**	14
Land conversion **(Agriculture, aquaculture, salt mining construction)**	12
Reduced water inflows **(Damming, climate change, re-channelling of waterways)**	8
Urban encroachment (settlement expansion, loss of protected status)	4
Pollution (solid and liquid waste disposal)	2

4.3.1.4 Health Dimensions of Mangrove Use

Research participants were asked questions about the numerous ways in which people use mangroves, and much of what was identified by the informants was related to the threats to mangroves previously highlighted and explained. A significant amount of this information was centred on livelihood activities relating to mangrove wood harvesting and the dependence on ecosystem support services for fisheries and other forms of biodiversity.

Wood harvesting is more pronounced in some communities than others. For example, in Anyanui, a community in the Volta Region, it is a major income earning venture, backed by locally initiated mangrove cultivation initiatives. Women cut wood from the mangrove forest fringes, whereas men tend to venture deeper into the forests using canoes in some instances, indicating a gender-based skew in magnitude of wellbeing influences that accumulate due to mangrove interactions and use. In other communities where fisheries are abundant, cutting of mangrove wood is relegated to a secondary and less important activity, and a thriving mangrove ecosystem additionally gives rise to greater shellfish diversity. In parts where wood harvesting does not occur at all, people exploit mangroves through gathering of other goods like molluscs, and profiting from tourism related recreational activities like birdwatching, kayaking, and canoeing. For example, an NGO representative had this observation to share:

> *"Some people also use mangrove areas for tourism. Once a while tourists come around for bird watching, canoeing, and kayaking through mangroves (for example in the Volta region. Some set up nice canoe drives within these mangrove ecosystems. They also set up hotels and build other tourism facilities close to some of these mangroves because it provides the opportunity for canoe safaris etc".*

The influence mangroves have on fisheries was commonly attested to, with the responses pointing to fishing as the main pathway through which humans interact with, and benefit from the mangrove environment. Several studies including Lee (1999), Beck *et al*., (2001), Blaber (2013) and Gajdzik *et al*.,(2014) have investigated this fisheries support function of mangrove ecosystems around the world. Taken together, such findings suggest that mangrove clearance and its role in triggering a cascade of structurally destructive ecological events, could play a pivotal role in fisheries decline. Vital nursery habitat support services are postulated to be catalysed by mangrove vegetation, through the provision of refuge for immature fisheries, and support for macrobenthos and detritus proliferation that sustain food chains (Manson et al., 2005). As such, loss of mangrove vegetation being linked to decline in fisheries catches and vice versa was expected, as confirmed in these comments from two conservation experts interviewed:

> *"The most common knowledge among communities is the fact that mangroves help them to get fish. This they have testified to on many occasions. They would often tell you that when the mangroves were present, fishes were bigger and they had more fish, but now that mangroves are gone, you do not get the fish".*

> *"Fishing is the dominant livelihood activity in the area, but during the lean season some also go into a bit of farming to supplement their incomes from fishing".*

This connection to fisheries has immense implications for local economies and for nutritional statuses of inhabitants in whose diet fisheries substantially feature. Fishing is a prominent venture in coastal communities in Ghana, although the returns tend to be seasonal in magnitude. Other activities, which incidentally account for a greater proportion of mangrove land conversion, are triggered to fill in the income gaps that arise outside the bumper fishing season of July to September.

Where land conversion is widespread, fragmented mangrove patches become an integral part of the undertakings necessitating the land use change. This suggests that people taking part in farming, aquaculture, and salt mining etc occasion indirect contact with nearby degraded mangrove patches in locations of this nature. Farming is limited to a small variety of crops, due to mangrove lands being unsuitable for a wider range, implying that mangrove land conversion for agriculture evokes limited economic and health returns. Given the limited avenues for generating farming produce, associated nutritional benefits for subsistence communities would still require augmentation from external sources. This raises the question of whether this alternative land conversion strategy is worthwhile, when weighed against the full complement of advantages presented by intact mangroves.

Also known as the ‘Acadja’ fishing method, brush park farming involves the use of mangrove sticks, which are more resistant to rotting in water, as ‘brush bundles’ to form an artificial spawning habitat for fish propagation (Figure 21). The fish are entrapped for a maturation period, and subsequently harvested when this time elapses.

Figure 21: Brush Park ‘acadja’ Stumps in the Keta Lagoon (Lamptey and Ofori-Danson, 2014)

This practice augments fisheries supplies in some locations when marine stocks dwindle, with positive consequences for incomes and nutrition. The mechanism has been more recently adopted to cope with a problem that is due in part to the cutback effects of mangrove loss on fisheries. Sadly, acadja aquaculture appears to be counterproductive, in the sense that it relies on harvesting juvenile mangrove wood. Hence, this practice tends to worsen mangrove ecosystem degradation by reinforcing a vicious cycle of mangrove vegetation loss and its effects, making an already dire situation worse. Eventually, all the mangroves are lost, so that even the ‘acadja’ strategy becomes difficult to sustain, thereby gradually eliminating this auxiliary livelihood and nutrition pathway from the health and wellbeing equation. Such an unfortunate outcome is currently being experienced in the township of Bortianor, within the Densu Delta Ramsar site of the Greater Accra Region, where nearly all mangroves have been depleted as result (Chasant, 2020). Residents perceive of the role of such practices as crucial even in the face of mangrove ecosystem degradation, and a conservation expert had this to say about the issue:

> *"Some even use mangrove wood for the 'brush park' system of farming because the local people do not see them as worth any other purpose aside making a living from".*

A similar challenge is exhibited in other communities where mangrove wood use for fish smoking is widespread. While respondents agree that mangroves are important for boosting fisheries, they also reveal how residents are conflicted by the competing desirability of mangrove wood for the purpose of adding value to the fish. These competing needs that people have of the surrounding mangroves, which in times past could have easily been enjoyed simultaneously under intact natural ecosystems integrity control mechanisms, can hardly be safeguarded now without adequate ecosystem interventions. Urban expansion and attendant pressures on freshwater drainage systems is one pattern of anthropogenic inference that could tilt natural ecosystem checks and balances out of gear and prevent mangroves from thriving.

Pollution from both domestic and industrial sources was also identified as a crucial threat to mangrove ecosystems, stemming from urban encroachment. Solid and liquid waste discharges have the potential to affect physico-chemical properties of the aquatic environment and surrounding sediment, threatening mangrove tree health, and habitat support functions for unique associated flora and fauna. The natural nutrient cycling abilities of mangroves can sometimes filter pollutants through chemical exclusion processes and sequestration within the sediment structure (Lewis et al., 2011). Chemical pollution can be problematic however, due to the fragile nature of wetland ecosystems, especially where contaminant load in unmonitored, and source of pollution is highly toxic. In the case of Ghana, not much is known about any monitoring of parameters for industrial waste discharges, especially since such activities are allegedly carried out clandestinely on the blind side of regulatory agencies. Two participants had this to say about waste disposal in mangroves.

> *"If you got to areas like Prampram, you see a lot of the mangroves being converted into waste dumping areas, people are using them as dumping grounds. Even in the Korle Lagoon area you see that happening there, turning mangroves into dumping grounds for waste*".

> *"The others are pollution from other developmental projects such exploration for oil and gas, which can lead to some of the mangrove ecosystems being contaminated by the oil spills. This is more prominent in the Western region, around the Nzema areas. Somewhere in the Muni-Pomadze area, there are companies and industries discharging they effluents into these mangrove areas and using them as dumping grounds. They connect waste ducts straight into the mangrove environment and discharge into them. You might not notice it if you do not intentionally make a trip to the specific site".*

Unfortunately, there appears to be no evidence of investigations which assess the attenuating effects of mangrove ecosystems with respect to pollution in Ghana. Further, the extent to which the associated risks might be transferred to flora, fauna and nearby human settlements remains unknown. It is thus difficult to discuss the pollution mediating effects of Ghana's mangroves within the context of any observed and potential human health consequences. No information that could serve as a basis for comparison to accepted thresholds and standards seems to be available, thus highlighting an outstanding gap in crucial knowledge. As a result of this less established Knowledge, lacking from both scientific and anecdotal points of view, interviewees had little insights to offer about the pollution attenuating benefits of mangroves. It was difficult to determine the extent to which related impacts have been felt. From the responses, it appears that only the ability of mangroves to physically sieve solid waste has been observed, as revealed in this quote from an academic expert:

> *"We did some work and found that especially the red mangrove roots serve as a sieve that prevents plastics from getting into the ocean. So that is what we looked at. But in terms of chemical pollution, we have not looked at that. But that is an interesting area that I would like to investigate".*

The prospects of phytoremediation of chemical pollutants, some of which could be of public health concern, however, seems to be an important consideration (Bentum et al., 2011). In respect of the significance of mangrove food goods and ecosystem services to communities, attenuation of chemical wastes would be beneficial to nearby communities who interact with such environments. A situation where such mediating processes are compromised would conversely present some health-related risks to nearby settlements, especially where pollution sources are not monitored or regulated. This interpretation was espoused in the sample response below:

> *"It is a matter of the level of contamination which the mangroves can tolerate. If not, they only pass it on to the other living organisms in the area and then we also get exposed to it in the food chain. I do not think I have seen any research to that effect".*

A summary or reported health impacts of human activities identified by interviewees is presented in Figure 22.

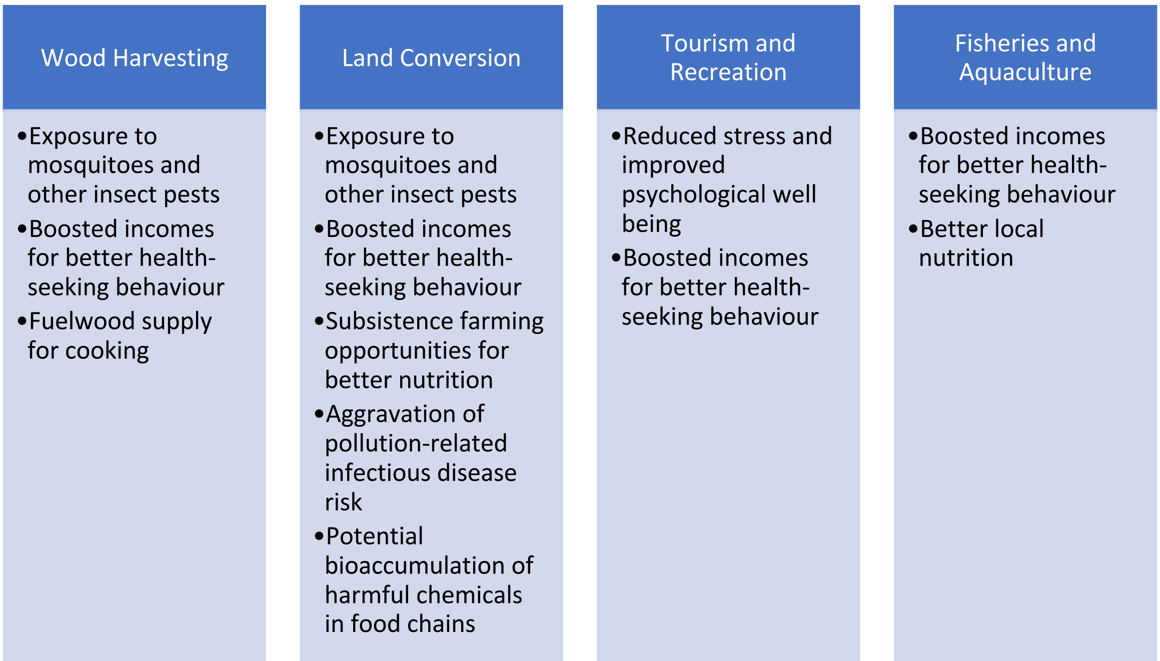

Figure 22: A summary of health Implications of key mangrove-impacting anthropogenic activities as Identified by Interviewees

4.3.2 HEALTH REWARDS OF MANGROVES ARE NOT SUBSTANTIAL TODAY (RQvi)

Interview questions regarding links between mangroves and human health were framed around 4 key health pathways of ecosystem services, based on a systematic review of relevant literature:

- Medicinal value of mangrove ecosystem goods
- Infectious disease influencing effects of mangrove ecosystem processes.
- Phytoremediation of harmful pollutants by mangrove ecosystem processes
- Nutritional benefits of mangrove ecosystem goods

Responses from health management respondents revealed an additional indirect health link, which is teenage pregnancy fuelled by the combined effects of mangrove-related rise in income levels, and gender disparities in distribution of this wealth. It emerged that unequal income levels lead to younger girls being enticed into early relationships with older wealthier men who provide for their financial needs. Most household incomes are held in trust by men on behalf of the household, and even sometimes considered to be their property, by virtue of their recognition as the heads of homes. Women are responsible only for the funds allocated to them by their male partners for housekeeping, except in situations where no male heads exist. This lack of financial empowerment often puts women at a disadvantage, thus compelling them to acquiesce to male pressures to enjoy any benefits of accrued wealth, be it in their own households, or the larger community. Female victims of sexual exploitation arising from this financial need are abandoned by their mostly fishermen sexual partners following pregnancies, leading to more mouths to feed in already deprived households. This, alongside the high birth rate impact of male aversion towards family planning interventions, accounts for a proportion of the marginally elevated malnutrition and anaemia cases observed in coastal communities. Two of the health experts had this to say regarding the links between mangrove-supported livelihoods and the outlined predisposing factors for high birth rate and its consequences:

> *"One other issue is the teenage pregnancy challenge among the coastal dwellers. These fishers return with money and then go in for the younger girls for transactional sex which sometimes results in unwanted pregnancy. In fact, my district has some of the worst teenage pregnancy challenges. The numbers*

are high in the district, and that is one major adolescent health issue, which is related to prevalence of socio-economic challenges and unequal wealth distribution".

"What we have also come to learn is that because the men usually go out to fish at sea for days before coming back home, they tend to view family planning measures as tools to facilitate promiscuity in their wives when they are away. Sometimes when they find out about family planning, they bring the women back for reversal of the procedures. Therefore, birth rates can also be extremely high, which impacts nutrition, health, and wellbeing especially of women and children in the poorest societies".

Therefore, while the presence and health of mangroves presents greater opportunities for livelihoods enhancement, the wellbeing and health gains can be demographically lopsided, degenerating into disadvantages in some instances. According to health professionals, women and children often bear the greater portion of this detriment.

4.3.2.1 Nutrition

Harvesting of mangrove wood and gathering of other ecosystem goods for consumption or for sale improves wellbeing, via both boosted incomes and direct contributions to better nutrition. Higher levels of income mean that people have access to more options for meeting health needs, such as ability to afford more nutritious meals and better healthcare services. Although fisheries are thought to be enhanced by the presence of mangroves in the Ghanaian scenario, this does not seem to necessarily translate into more fish protein in local diets. There is an apparent preference to maximise economic gains by reserving the best parts of their daily catches for market sales. Nevertheless, residents believe that they eat more fish during the bumper fishing season. Applying preservation methods like smoking, salting, and drying ensures that stocks last beyond natural periods of freshness, as illustrated in this quote from a local resident's comments:

"We eat a lot of fish, so the mangroves help with our wellbeing. In fact, it will be hard to find a household where mangrove fish is not consumed. There is also a lot of shellfish and snails. The fish can either be smoked or consumed fresh, but

usually the smoked ones are sold at the market because they have longer shelf life. The less attractive fresh fish is saved for home cooking, and the larger ones or delicacies are sent to the big markets for sale. Sometimes if they have not all been sold and they are not so fresh anymore, they are smoked or fried or eaten at home".

4.3.2.2 Medicines

Although medicinal use of mangrove ecosystem resources was not spontaneously named by respondents as a health-dimension of mangrove use, responses to direct prompts regarding that subject affirmed the existence of herbal medicines for treating common ailments. Conditions like fevers, wound infections, arthritis, and general malaise were mentioned in relation to mangrove-sourced herbal remedies, but there was no indication about the specific mangrove species that serve as ingredients for such preparations. If people are unable to readily point out the mangrove resources that are relied on medicinally, then a lack of familiarity and thus inconsistent use is implied. Notwithstanding this lack of specificity however, anecdotal accounts point to various aqueous and fume extracts of mangrove leaves and barks being used as traditional purgatives and in the treatment of fevers. As two interviewees explained:

> *"I was told by one of the old men, an opinion leader in one of the communities called 'Woarabeba' in the Central Region, that in the olden days they used to use the leaves of mangroves to treat leprosy, and then also after women had given birth, they boil the leaves and make them drink it. It makes their 'belly strong again', as they put it. So, it is of medicinal value to them as well. People would also take mangrove barks, boil it along with some lime and drink it to purge themselves. They are used to treat all sorts of diseases with mangroves in the past. But lately, due to modern health practices, that aspect is dying off".*

> *"There are people in the town who have the knowledge, and you can go to them for help. Maybe there are some mangrove leaves for treating some conditions, but I do not know much about it. What I know is that when you boil the barks of some trees, you can use it for treating fevers. Then there are leaves meant for healing wounds and cuts"*

The efficacies and optimal dosages of such preparations are unclear, yet residents are confident that these preparations are efficient at treating the stated conditions. Their beliefs are consistent with others held among mangrove populations in other tropical mangrove locations, the only difference being that bioassays have been conducted into some of these preparations used especially in Southeast Asia. In other parts of the world, medicinal value has been validated in the bioactive metabolites of aqueous and organic extracts of mangrove parts such as leaves, bark, or roots, as well as in associated actinobacteria and fungi. Several bioactive compounds have been isolated and identified from numerous mangrove tree species and associated flora, with varied demonstration of antibacterial, antifungal, anti-inflammatory, antipyretic, and antidiabetic effects among others (Bandaranayake, 2002). Unfortunately, no such information was espoused in the interview responses or in academic literature in relation to Ghana.

4.3.2.3 Infectious Diseases

The reputation of mangroves as disease reservoirs seems to hold true according to the views gathered in this research. Several interviewees made references to insect vector and pathogenic disease prevalence in mangrove areas. Abundance of mosquitoes was the most underscored disease-related disservice from mangrove ecosystems, emphasized by every participant. The consensus is that mosquito numbers are higher within mangrove forests, with the aquatic characteristics of the mangrove ecosystem offering a unique advantage for breeding. While the prevalence of the malaria-causing plasmodium parasite is yet to be studied within mangrove mosquito populations anywhere in the country, one respondent mentioned that investigations do not suggest that mangrove-dwelling birds like egrets act as zoonotic sinks for the malaria parasite. The nuisance status of numerous mosquitoes breeding within mangroves was well acknowledged. Other insects are occasionally encountered too, but the mosquitoes stand out due to their larger sizes and all-day action, which sets them apart from their smaller, mostly night-biting household counterparts. This observation aligns with the conclusions drawn by Takken et al., (1998), in relation to the *Anopheles gambiae* complex of mosquitoes which are most prevalent in Ghana. The authors pointed out that larger mosquitoes emerging from nutrient rich environments like mangroves are less aggressive in seeking hosts for bloodmeals, having fewer nutrient deficits than their smaller counterparts. Mosquitoes are an obvious nuisance, as explained by four different interviewees in these excerpts:

> *"The water helps the mosquitoes. Because it is not flowing water. The water gets there at high tide, but upon flowing out not all the water flows back. We have some stagnant water and pools left behind, and that mostly supports the breeding of the mosquitoes I know that a lot of the times when we go for planting you can see a lot of the larvae in the water".*

> *"What we were doing was to sample the bird species to see if they were hosting plasmodium parasites and whether the mosquitoes use the birds as 'storage for the parasites. I have never seen mosquitoes that big. The question is where would these mosquitoes go when they need to feed in the night? 'Sodom and Gomorrah' is the nearest slum. Now you go to La-Dadekotopon area, the people of La and Teshie are the immediate hosts for them to feed on".*

> *"They are everywhere, including the nearby mangroves. When you ride in the canoe, you can sometimes see them dispersing in their numbers when the water is disturbed. The only difference is that they tend to be bigger around the mangroves. One thing I have noticed is that those big ones are slower-moving, and do not bite as aggressively as the smaller ones in the village".*

> *"There are other insects in the mangroves too. Some of them bite and sting, but I do not know if they also give any diseases. But they are certainly a nuisance".*

The other disease risk that was identified as being linked to mangroves is diarrhoeal infections arising due to faecal pollution in the mangrove environment, which some still regard and treat as wastelands. This was tied to the open defaecation phenomenon that is peculiar to coastal areas, and which health research has identified as a potential warning for the emergence of diarrhoeal epidemics. Uncontrolled deposition of faecal waste was speculated to be responsible for the proliferation and transmission of pathogenic agents, via direct contact with contaminated water, and through the consumption of compromised food goods. Outbreaks of diarrhoeal infections, such as cholera, have thus been characteristic of coastal settlements, although sensitization programs have led to behavioural changes and thus a decline in occurrence. The following assertion was made by the health staff interviewed:

> *"One thing I have noticed however is that we tend to have more diarrhoeal cases reported in the coastal communities. This has been attributed to the unfortunate phenomenon of open defaecation, which poses a health risk to people in those areas. That is one major challenge along the coast, and this can easily spread diarrhoeal diseases. Luckily, we have not reported any cholera cases in a while, but some time back in 2013 or so, there was a wild outbreak".*

This observation is consistent with the potential health consequences of estuarine microbial load defined in some scholarly work including Grisi *et al*., (2010):

4.3.2.4 Bioremediation of Pollution

There is currently no discernible knowledge regarding the phytoremediation properties of Ghana's mangrove ecosystems, academic or otherwise. While pollution was recognized by participants as being predominant in some mangrove environments, no data exists regarding the extent to which harmful discharges or wastes are attenuated by the ecological processes occurring within mangrove ecosystems. On the contrary, there are indications that tree die-offs are initiated and aggravated by high aquatic and sediment contamination resulting from pollution. This suggests the possibility of transmission of harmful contaminant elements though food chains and across trophic levels, as intimated in these comments from two conservation experts:

> *"Again, we have pollution – people dumping directly into lagoons harbouring the mangroves, destroying the lagoon habitat. When the water is polluted, the mangroves begin to die".*

> *"It is a matter of the level of contamination which the mangroves can tolerate. If not, they only pass it on to the other living organisms in the area and then we also get exposed to it in the food chain. I do not think I have seen any research to that effect".*

These assertions are substantiated by some accounts about pollution within wetlands. Mangrove loss along the Fosu Lagoon in the Central Region of Ghana reportedly gave rise to extremely high pollution levels and eutrophication within it, resulting in its subsequent designation as a 'dead zone' (UNEP, 2006). Samples tested from that lagoon showed that run-off from nearby activities (sanitary wastes from medical institutions and boarding schools, leachate from automobile servicing sites, etc.) introduced elevated levels of cadmium, nickel and zinc which pose potentially serious threats to the consumers of fish sourced from it (Bentum et al., 2011). This, the writers believed, was attributable to the absence of the basin mangroves of the area along with their nutrient processing abilities as described in Clough *et al*., (1983). Therefore, there appears to be some connection between mangrove loss and toxic bioaccumulation in biodiversity under contaminated conditions, although not directly reflected in participant responses.

The evolving nature of health-related mangrove ecosystem goods and services as identified by interviewees is captured in Table 13.

Table 13: Summary of changing characteristics of health-related mangrove ecosystem services

MANGROVE ECOSYSTEM GOODS AND SERVICES			
MEDICINES	**NUTRITION**	**POLLUTION BIOREMEDIATION**	**INFECTIOUS DISEASES**
Diminishing reliance on herbal products	Support for fisheries, although some not consumed locally	Mangroves still treated as wastelands in some areas	Habitat support for nuisance insects prominent
No medicinal mangrove resources could be readily identified	Mangrove land conversion for agriculture is marginal with limited returns	Waste discharges into mangroves go unmonitored	Mosquitoes from mangroves not believed to transmit malaria
Disappearing knowledge about medicinal value of resources	Fuel wood for cooking and adding value to fisheries (smoking techniques for preservation)	Mangrove roots are known to trap solid wastes	Dumping sites for wastes including faecal matter (high gastroenteric disease risk)
Limited information about efficacies and proper dosages	Suitable aquaculture conditions and resources	Nothing reported about mangrove interaction with chemical pollutants	Some mangrove-dwelling fauna found to not be zoonotic for malaria parasite

4.3.3 INTERVENTIONS MAKE A DIFFERENCE (RQvii)

Most interventions highlighted in participant responses were intended to target mangrove conservation and public health concerns separately, and do not appear to have been informed by knowledge about how one sector relates to the other. On one hand, mangrove restoration projects have been pursued purely on grounds of wetland ecosystem conservation, whereas community initiatives are driven by the prospects of better economic returns. On the other hand, public health interventions have always come in the form of formal implementation of national and regional health policies, with no indication of local mangrove ecosystem underpinnings. However, these unique sector interventions can elicit overlapping consequences. For example, the universal health insurance scheme and greater number of health facilities might diminish reliance on mangrove ecosystem goods for medicinal purposes by offering therapeutic alternatives. Ecological interventions primarily aimed at preserving or expanding mangrove forests could also potentially increase economic benefits of mangroves, thereby empowering people to access wider varieties of health-seeking opportunities. Some of these interdependencies were revealed in the interview responses.

4.3.3.1 Ecological Restoration

The previously highlighted benefits that arise form living close to mangroves typically dwindle following ecosystem degradation and are conversely amplified following restoration attempts. In particular, the enhancements that fisheries and tourism experience go a long way to revamp local economies. Such consequences promote the embracement of restoration projects and serve as motivation for community involvement. In some instances, residents are even driven to solicit for such projects in their localities based on discernible benefits enjoyed in other neighbouring beneficiary locations. The impact of mangroves on community wellbeing is therefore tied with restoration knowledge, project opportunities and success rates. This wellbeing link is further strengthened by the fact that donor agencies usually inculcate livelihoods diversification training programmes into the design of mangrove restoration projects, to lure interests away from degradative activities. In other words, as steps are taken to reverse mangrove ecosystem degradation, preventive measures are simultaneously enforced to ensure that these projects are not undermined by unabated exploitation of mangrove resources. As one wetland management expert explained:

> *"It looks like they really appreciate the importance of mangroves and the difference that ecosystem restoration makes. Economically it has improved the fisheries quantities there, because the communities attest to the fact that they sometimes have fishes under the mangroves, so those who are into fishing are happy. For a project in 'Tsokome' for example, as part of the engagement process, community members told the project implementers to plant mangroves for them for this very reason. That tells you how strongly they link mangroves to success of their fishing activities".*

This demonstrates the fact that residents are aware of the difference that ecological restoration makes and are additionally conscious of the benefits that could potentially be lost if these intercessions are impaired.

4.3.3.2 Public Health Advancement and Attitudinal Shifts

In this section, informants were asked to comment on the various interventions and reforms that have been channelled formally via the public health sector of local government, and the outcomes of same. The responses point to evolution of mainstream healthcare infrastructure, with access and patronage being on a steady ascendency. This trend was attributed to a cocktail of factors, key among which is the greater government and donor investments in healthcare facilities, and a revamp of supportive human resource framework for the health sector. Moreover, there has been an institutionalisation and strengthening of a National Health Insurance Scheme to promote affordability, and a higher literacy rate which has diversified health-seeking behaviours. Taken together, the result of these sector interventions is the relative abundance of health centres, better affordability of healthcare services, less scepticism about western medicine and therefore more widespread patronage. One resident had these sentiments to share on the matter:

> *"These days it is easier to just go to the health post, because they have better medicine, and mostly we don't have to pay for them anymore".*

The roll out of a Community Health Program has seen health facilities being set up at the settlement level across the country. Referred to as 'CHPS compounds', these centres are staffed by community health nurses, physician assistants (PAs) and occasionally visiting doctors who administer primary services. These typically comprise testing for malaria, childhood immunizations and dispensing of basic medications for malarial fever, diarrhoeal infections, injuries and general aches and pains. Occasional outreach programs are organised to bring strategic health services like immunizations to the doorsteps of households, and remote communities such as the island settlements in the Volta estuary area. More serious conditions are usually referred to polyclinics and district hospitals, implying that access to formal healthcare is limited at the rural level as compared to more urban townships. However, across the rural settlements along the coast, and within those found elsewhere in the country, interventions, access, and provision with respect to healthcare resources exhibit similar patterns. A local resident and a conservation expert had these insights to share:

> *"We have some health posts here for getting medicine. Sometimes when you have a fever or diarrhoea, they give you treatment. Especially the children. They always come around for immunization and advise us to come over, so people go there a lot".*

> "*Sometimes also they had the health nurses going into the communities directly, because these compounds are usually just a few kilometres away from the community, but they were always accessible. Sometimes extra health personnel would directly be deployed to community health centres to engage in activities like immunization".*

On the other hand, and following a reversed trend, reliance on traditional medicine persists but to a reduced degree in mangrove communities. This alternative is offered via the services of a few specialists of indigenous medicine, to whom awareness on the historical usage of local remedies has been handed down from one generation to the next. Such custodians of traditional medicinal knowledge are called upon to set broken bones, treat wounds and to act as birth attendants in lieu of same services from mainstream health personnel. They tend to have practices that are far removed from those of trained health services personnel, and these two vastly distinct types of practitioners rarely see eye-to eye on what constitutes an appropriate therapeutic approach. However, there are instances when they work in tandem or complementarily, to meet varying degrees of health needs. These two comments from district health staff of the Ministry of Health, followed by a third quote from a resident, provide some relevant context:

> *"The other thing is that some have their 'spiritual fathers and mothers' who offer prayers and alternative remedies for them, and in the facilities such people would not be allowed to be in the delivery room for example. Unfortunately, sometimes the mothers want such people to be with them when they are in labour, leading to misunderstandings. Sometimes they even want concoctions smeared on their bellies etc. There are always some conflicts depending on beliefs, and those are some of the challenges".*

> *"In those areas most of the time they have the traditional herbal medicine practitioners, birth attendants, traditional bonesetters etc. In case someone has a fracture, they go to that person to set the bone. They would then tie the limb up, and then he observes the patient until the bone heals. If it is overly complicated, for example bone piercing through the flesh, they find ways of sending the patient to the nearest health facility. All such practices involve use of local plants, but I am not sure which."*

> *"My grandmother used to be an expert in local medicinal preparations, and one thing she used to say all the time was that the herbalist does not reveal all her secrets. They used to pass their skills on to designated members of the family, and anyone who needed advice would directly go to them or their apprentices. It is rare to find a community where everyone has in-depth knowledge on the application of herbal medicines. Personally, I have been treated with such preparations several times, but it would be dishonest of me to claim to understand the how they are made. We always talk to those who have the knowledge and ask for their recommendations and help".*

Health data tracking at the district level, and based on patronage of health centres, does not demonstrate any peculiarity in terms of commonly reported health concerns. No unique ailments or conditions that stand out for people who live in mangrove communities were indicated, with available data suggesting similarities with non-mangrove areas. As such malaria, upper respiratory tract infections, diarrhoeal diseases, malnutrition, and anaemia are the most recorded health conditions that people seek treatment for.

> *"What I have experienced in the past 4 years has not shown any peculiar trends. If you compare the data to other districts in the middle belt or northern regions, inland forest zones etc, they are the same typical issues".*

As these circumstances are no different from those in other rural communities across the country, no unique targeted medical interventions have been necessitated for mangrove communities. Malaria is the most common disease, responsible for the greater proportion of morbidity and mortality rates and giving rise to most anaemia cases reported. Like those rolled-out in most rural and peri-urban areas, general interventions include awareness creation programs, distribution of insecticide treated nets, maternal prophylactic therapy and larviciding projects. A local resident had this to say about mosquitoes and malaria, and as intimated by another respondent in the ensuing comment, certain formerly prevalent conditions are no longer observed at the local level.

> *"Mosquitoes are everywhere these days. We use mosquito nets in my house because they were given to us to protect us from the fever (malaria). When you sleep at night that can keep you safe, but in the evenings when we spend time together outdoors, we often get lots of bites before we retire. My body is used to it now".*

> *"Sometimes they also deal with injuries and stomach problems. Some of the diseases that we used to see in the past, like yaws and leprosy, are beginning to vanish. Because of the vaccinations that the babies get, young people today are*

stronger than we used to be. In my time it was rare for one's children to all make it to adulthood, but that has changed now".

While malaria is the most common ailment reported for treatment, other socio-economic outcomes play in role in general health and well-being. As such, healthcare professionals were eager to use the opportunity to throw light on some health concerns which although not directly considered to be ill health conditions, were undesirable had some indirect relationship with livelihoods and income levels. One such curious revelation was the assertion that the healthcare system deals with surges in teenage pregnancies and associated complications, which are widespread in coastal communities, including those where mangroves are found. Early childbirth leads to truncation of formal education of young girls, early marriages where they have no means of personally fending for themselves, and to their offspring being ill catered for. As previously explained in respect of mangrove communities, this phenomenon is often observed where men are unequally favoured by mangrove-related livelihood enhancements to the detriment of women. This is one of the unintended consequences of beneficial ecosystem interventions pertinent to coastal communities presented in Figure 23.

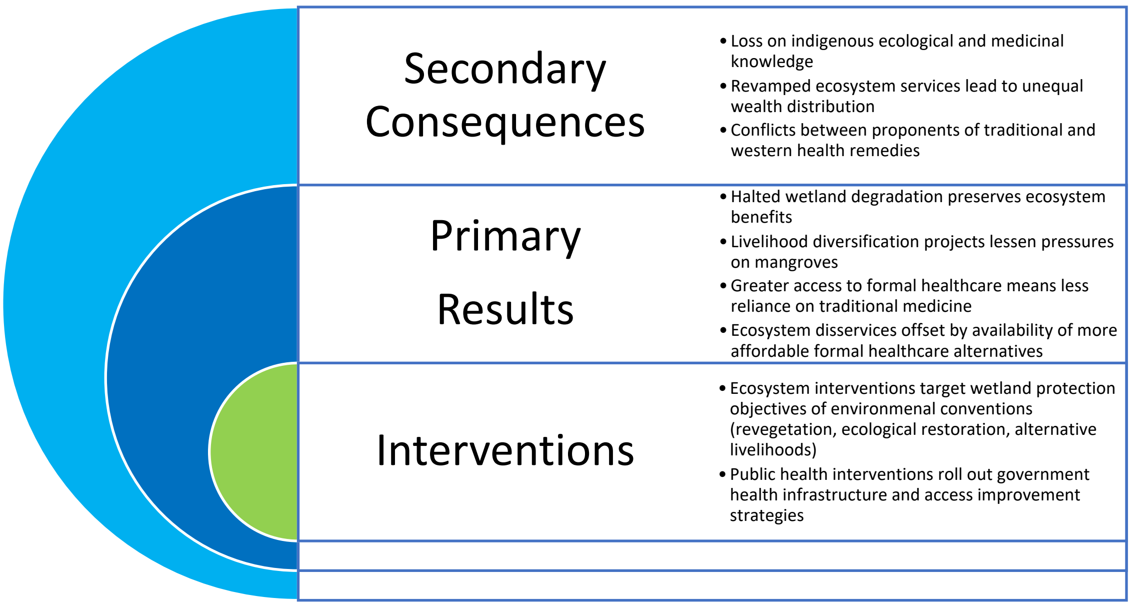

Figure 23: Summary of Primary and secondary consequences of interventions

4.4 CONCLUSIONS AND IMPLICATIONS

The aim of this study was to explore relationships between mangroves and human health from the viewpoints of a variety of Ghanaian key informants. Evidence, in the form of responses to semi-structured interview questions, was obtained from residents of mangrove communities in addition to experts/practitioners from the conservation, health, academic, media and NGO sectors. Mixed ideas were expressed in relation to changes that have occurred in the states of Ghana's mangrove resources, the ways in which people interact with them, and the health impacts thereof. Perspectives also emerged regarding ecological and health sector interventions instituted alongside these changes, and how health experiences have been affected by this interplay of events.

Although environmental change and over exploitation have intensified ecosystem degradation, mangroves have always been an important feature in culture and livelihoods of coastal communities in Ghana. Presently, commitments towards international wetland protection and restoration obligations have spurred some corrective initiatives directed at halting degradative activities, including sensitization and restoration programs. Such initiatives remain insufficient to deal with mounting pressures faced by mangroves, partly due to the nature of land tenure and governance structures which limit the extent of government control over the fate of mangrove lands. Thus, the rate of mangrove loss has a greater chance of being curtailed via entrenchment of bottom-up sustainable use practices, some of which are already employed, and are easily reproducible and scalable.

The foremost value of mangroves for coastal communities in Ghana evidently lies in provisioning and supporting ecosystem services, which are diminished following degradation, and palpably boosted following restoration. Within the mix of mangrove ecosystem services identified in key-informant responses, the most outstanding health-related benefit lies with supporting services for fisheries used as food. For this benefit, there is a consensus among respondents, further evidenced by local appreciation for mangrove restoration projects. To a narrower extent, provisioning for medicinal goods as well as regulating services for pollution control were also identified. Absence of concrete knowledge regarding specific constituents and efficacies of mangrove-sourced medicines, along with lack of monitoring of pollution levels within mangroves, accounts for the limited health links drawn from these two pathways. Mangrove regulating services for control of infectious disease agents were the least appreciated especially among health and academic sector key informants, who regard the risks of enteric pathogen and mosquito proliferation as disservices to human health.

It was evident in this study that restoration, revival of indigenous knowledge and sensitization initiatives could be vital in preservation of both obvious and untapped health-enhancing potential of mangroves, which are currently perceived to outweigh disservices. Not only is diminishing local knowledge affecting appreciation of the importance of mangrove benefits such as medicinal products; it is also erasing the available expertise for sustainable ecosystem management. While some communities retain a strong mangrove replanting culture, others have experienced progressive mangrove loss, necessitating livelihoods diversification away from the mangroves. The public health interventions resulting from central government policies have been instrumental in providing alternatives to offset dwindling health benefits accompanying mangrove loss. A universal health insurance scheme, along with revamped health infrastructure and human resource base, has brought formal healthcare services and thus better health outcomes closer to the doorsteps of previously marginalised populations. However, because roll-out of these initiatives have not been uniform across urban and rural landscapes, there are transitional shortfalls in coverage that could potentially be bridged via retention of traditional remedies. Mangrove-related livelihood enhancement windfalls should be equitably dispersed to arrest some health-impacting socio-economic burdens that disproportionately affect women. For some coastal and mangrove communities, such realignment could be just as beneficial to community health as mainstream health interventions.

Missing academic knowledge about pollution attenuation impacts and medicinal value of Ghana's mangroves means that ecosystem intervention consequences on these potential benefits cannot be sufficiently assessed. Addressing these knowledge gaps could open pathways for development and application of useful bioactive compounds, and for setting local pollution regulation standards that minimise health risks posed by mangrove pollutants and pathogens. The results of this study confirm though that revegetation, as a key catalyst for reversal of ecosystem degradation, enhances fisheries support services of mangroves. This suggests that ecosystem interventions at the very least initiate the ecological integrity improvements required to holdup ecosystem services, especially those that support human nutrition. For communities enjoying an improvement in ecosystem services, there needs to be a favourable balance of regulated mangrove use that does not compromise the sustained provision of services linked to health. For example, consistent replanting regimes must accompany harvesting of mangrove wood for the purpose of value addition and preservation of fish via smoking.

Although public sector health interventions have been instrumental in offsetting some of weakening links between mangroves and health outcomes, risk of infectious disease such as malaria remains worrisome. The nationwide prevalence of malaria in Ghana makes it difficult to implicate mangrove mosquitoes in present malaria pervasiveness reported in mangrove communities. Nonetheless, mosquitoes are nuisance insects readily associated with mangroves. The absence of malaria parasites in some reported zoonotic assessments of mangrove wildlife, and residents' insistence that mangrove mosquitoes "do not give malaria", together highlight a research blind spot. Further investigation of malaria parasite prevalence amongst mosquitoes sampled from mangrove environments, and documentation of mangrove modulation of vector behaviour relative to nearby human settlements, are necessary. Such enquiries would reveal more clearly if the mosquito abundance reported in Ghana's mangroves necessarily translates into an aggravated malaria (and therefore health) risk that is not sufficiently tackled under the national malaria control strategy. This could inform formulation of effective vector control strategies which can counterbalance mangrove infectious disease risk. Such cross-sector plans would preserve the best parts of mangrove ecosystem management, while minimising disservices of same, via customised streamlining of vector control interventions. In lieu of such specialised information, CHAPTER 5 of this study explores how currently observable mangrove-related ecosystem conditions work in conjunction with malaria preventive strategies to influence self-reported malaria incidence dynamics in Ghana's Volta estuary.

CHAPTER 5: MALARIA INCIDENCE IN AN ERA OF ECOSYSTEM INTERVENTION – ASSESSING THE CONTRIBUTIONS OF THE MANGROVES

5.1 INTRODUCTION

Environmental protection is one of the key requirements for sustainable development, with consequences for natural resource utilisation and human wellbeing (UNGA, 2015). When natural ecosystems are functioning fully, biodiversity and human populations have more positive preservation and survival outlooks. Interventions that target environmental restoration, with the view to protecting benefits supplied by nature, are therefore important for fostering integrity of social-ecological systems. Particularly in situations where environmental degradation has been found to have initiated systematic decline in vital ecosystem services, management interventions can be crucial in achieving trend reversal (Walton et al., 2006; Crona and Rönnbäck, 2005; Bosire et al., 2008). To evaluate the success and value of such interventions, their impacts on various facets of wellbeing, including and more curiously, on aspects for which they were originally not targeted, should be assessed. This could be crucial for revitalising ecosystem types that have historically not been accorded much value or policy attention, but which have now been found to be important, such as wetlands.

As indicated in the Millennium Ecosystem Assessment, the impacts of ecosystem integrity transcend the wellbeing of the ecosystems themselves, and contribute more widely into contiguous social-ecological systems (MA, 2005). In this regard, aspects of human wellbeing, such as states of emotional and physiological health, depend on conditions of natural environments, composed of interconnected ecosystems and their processes (Bauch et al., 2015; Bayles et al., 2016). Investigations of impacts on human wellbeing components could therefore complement direct ecosystem monitoring, offering an extra means of evaluating ecosystem management practices and interventions, and of identifying improvement opportunities for same. This is especially relevant in the cases of ‘neglected’ environments, such as those that supply marine and coastal ecosystem services (MCES), which receive comparatively less attention. In the assessment of non-economic impacts of ecosystem interventions, these MCES, including services from wetland ecosystems like mangroves and salt marshes, have not received as much focus as those services supplied by terrestrial ecosystems (Barbier, 2012).

While several theories have been proposed to link mangrove ecosystem goods and services to health outcomes in human populations, available evidence remains fragmented. A review of the literature uncovers a variety of health-related enquiries into how mangrove resources yield health benefits (CHAPTER 3). For example, bioassays into medicinal applications of mangrove sourced compounds point to a variety of antimicrobial action, in addition to the potential to relieve some physiological ailments in-vitro (Bandaranayake, 2002). Mangrove forests have also long been recognised as shoreline protectors against extreme weather and coastal events capable of displacing communities, and triggering incidents that could lead to health decline (Marois and Mitsch, 2015). The role of mangroves in promoting fisheries diversity and abundance is another area that has attracted significant researcher interest (Lee, 2008; Beck et al., 2001), with significant implications for the nutritional aspects of human health in coastal communities. Other health-linked investigations conducted on mangrove ecosystems centre on their pollution attenuation properties, spiritual and recreational value, and worth for social cohesion (Friess et al., 2020). Unfortunately, the studies mentioned afore have been geographically limited, and have not been sufficiently extended to conventional and emerging infectious disease risk, which presents some of the biggest threats to physiological health and wellbeing in the developing world. Especially with respect to Africa's mangroves, little is known about how they influence health experiences, or the promise they hold for mitigating some of the biggest health concerns on the continent, such as malaria. Beyond isolated accounts of insecticidal and larvicidal properties of mangrove resources against malaria vectors (Patra and Thatoi, 2011), little is reported in the literature regarding how non-climate-related ecosystem transformations influence susceptibility to the disease on the continent. Nonetheless, it has been shown that the nature of surrounding ecosystems affects mosquito diversity and abundance (Claflin and Webb, 2017); and that biological control processes against vector mosquitoes in mangrove ecosystems hold promise for reducing health risks (Griffin and Knight, 2012).

Informed by the principle of ‘wise use’ (Ramsar, 2014b), wetlands are conserved in Ghana by virtue of the country’s ratification of the Ramsar Convention on Wetlands, under which sustainable use of wetlands and wetland resources must be promoted. Some of these wetlands have been designated as ‘Ramsar sites’, under the oversight of the Wildlife Division of the Forestry Commission of Ghana (Figure 24). In addition, a ‘Forests and Wildlife’ policy established in 1994 covers activities related to such sites, and is intended to protect wildlife species therein (Derkyi, 2007). Among the key activities undertaken by the Wildlife Division, with support from the non-governmental and informal sector, is ecological restoration and revegetation of mangrove ecosystems.

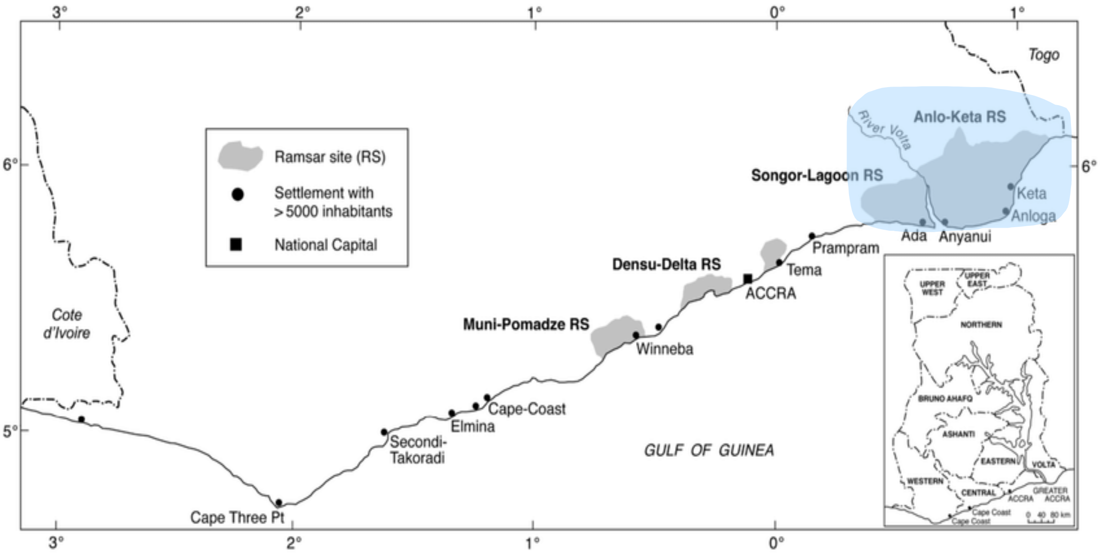

Figure 24: Map of the coast of Ghana showing locations of designated ‘Ramsar Sites’ (Dovie, 2003). The region shaded in pale blue indicates where the study sites are situated.

In 2013, the Songor Ramsar site was additionally registered as a UNESCO ‘Man and Biosphere’ reserve (AfriMAB, 2013), further highlighting its economic, ecological, and recreational value. Conservation and rehabilitation activities have typically been undertaken and evaluated with the goal of scientifically advancing man-environment relationships. Most evaluations have thus involved physically and chemically observable parameters such as changes in wildlife, tree canopy cover, aquatic drainage, and salinity. These types of changes tend to be indicative of the cascade of degradative conditions linked to biodiversity and habitat loss, pollution, and invasive species, among others. Such assessments have usually been undertaken because they are focused directly on the ability of ecosystems to continue supplying goods and services of intrinsic and economic worth to humans and the environment within the 'wise use' context (Ramsar, 2014b).

This study provides fresh insights by investigating the links between states of mangrove ecosystems and human health, using experiences with malaria, a prevalent natural environment-related communicable disease, as proxy for human health. This choice was made because malaria as a health condition has been cited as having consistently been responsible for the most deaths and disabilities for all combined age groups in Ghana since 2009 (IHME, 2021). Qualitative Comparative Analysis (QCA) is the analytical method of choice and is used to test the causal role played by mangrove ecological conditions on malaria outcomes based on available theoretical knowledge. Developed by Charles Ragin as a comparative method for assessing causal relationships, the QCA research process embodies desirable characteristics of both variable-oriented (e.g., regression analysis) and case-oriented (e.g., case study) data processing strategies (Ragin, 2009). Instead of a net-effects approach, which measures the direct or indirect effects of one variable compared to others, this method estimates what configurations of case conditions may be necessary or sufficient to elicit an observed outcome. Taking the concurrent role of non-mangrove interventions into account, an examination of the specific conditions (or combinations of conditions) responsible for the lived malaria experiences in these communities is undertaken. In doing so, the direct and incidental role played by the presence and state of proximate mangrove ecosystems on malaria and thus health outcomes are identified. The conclusions attained are, however, based on the peculiar assumptions made in the specific case context, and arguments made in explanation of the empirical observations are based on contemporary theories which are liable to future refinement.

5.1.1 Research Questions and Design

This study assesses the health impacts of mangrove ecosystem interventions by examining perspectives of people living in various coastal communities in Ghana. The overarching aim is to explore perceptions of people living in a variety of mangrove communities regarding how physical health, as signalled by malaria infection trends, has been impacted over time. The following research questions are addressed in the study:

RQviii. What are the available theories and empirical insights about how malaria could be influenced by ecosystem processes in mangroves?

RQix. What are local perspectives on changes in both mangrove ecosystem characteristics and malaria incidence trends over time?

RQx. How do mangrove ecosystem-related and/or other interventions work to influence observed malaria changes in the case study population?

RQxi. What role do mangroves play in the potential causal structure revealed via question x, and what are the implications for local ecosystem and malaria risk management?

Sampling was conducted in communities within the Songor and Keta Lagoon Complex Ramsar sites and surrounding towns in Ghana, based on both common and distinguishing characteristics. This location was chosen because it harbours mangrove patches that vary in extent of degradation and management regimes. Two of the communities have healthier, progressively revegetated mangrove forests (Anyanui and Tunu), which like the one community with a restored mangrove plantation (Obane), are anticipated to have better ecosystem integrity than the degraded mangrove community (Azizanya). A fifth community with no mangroves (Salo) is included as a control site, to capture perspectives about malaria incidence under zero-mangrove conditions. Demographically, these case study locations are similar in livelihood activities, income levels and other population characteristics, differing only in the presence and/or state of nearby mangrove ecosystems. In the first layer of analysis, descriptive statistics are applied to questionnaire results to compare perspectives regarding malaria incidence with hospital-confirmed malaria data. This is aimed at ascertaining the validity of the viewpoints expresses at the community level, regarding how the magnitudes of malaria infections have evolved over time. In a second layer of QCA assessment, the causal relationship between mangrove presence and/or ecosystem health and malaria incidence is estimated using fuzzy-set QCA analysis. Following this computational step, the theoretical bases of resultant causal configurations are discussed by reviewing the qualitative underpinnings of these links, based on theory-embedded explanations relative to participant malaria experiences over time.

5.1.2 THEORETICAL AND CONCEPTUAL FRAMEWORK

5.1.2.1 Mangrove Ecosystem Integrity

Most assessments of 'ecological quality' within ecosystems are influenced by what drives evaluators, and motivations for assessment tend to have human welfare connotations (Paetzold et al., 2009; Müller and Burkhard, 2005). Thus, a consistent definition and characterisation of what constitutes desirable ecological quality across all spheres, which would engender widespread acceptance of related public policy, remains elusive. Some other notable alternatives framings, such as Karr's 'biological integrity' and Rapport's 'ecosystem health' concepts, have been put forward to enhance theoretical bases for assessing how well ecosystems are functioning (Section 2.2.1). These ideas focus on how close ecosystem functioning is to what would be considered more 'natural', either under undisturbed conditions or by considering historical state of that same ecosystem (Tierney et al., 2009). The key measurable properties for making such determinations are those related to ecosystem composition, structure, and function (e.g., as listed in Table 3), again, requiring an almost unattainable consensus about what is optimum (Foley et al., 2005). Moreover, because what is considered a valuable change in ecosystem integrity depends on who is asking the question, conservation goals may not always solve every outstanding problem. For example, as part of a climate strategy, a forest suffering effects of invasive species on biodiversity may not be considered threatened if its ability to act as a carbon sink is not significantly compromised.

Mangrove restoration in Ghana, whether externally initiated or community based, is directed either at meeting targets of conservation treaties, or at protecting the provision of provisioning services. In general terms however, measurable ecological characteristics (such as connectedness, productivity, and food webs) are expected to improve over time, provided anthropogenic disturbances are controlled (Müller and Burkhard, 2005). In the current study therefore, ecosystem integrity is assumed to undergo progressive improvement with time following revegetation of deforested mangrove ecosystems. In other words, reforested mangroves are considered to have better ecosystem integrity than degraded mangroves. Evidently, the concept of 'ecosystem services', which is reflective of perceptions around the quality of nature's services to humans (De Groot et al., 2002) is invoked as part of the conceptual framework for estimating ecosystem integrity. For this reason, perspectives of local inhabitants are relied upon in fulfilling this aspect of the enquiry, by probing how benefits derived from mangroves have changed following revegetation.

5.1.2.2 Mangroves and Anopheline Disease

Malaria epidemiology is altered when environmental factors promote vector breeding conditions such as stagnant water and warmer temperatures. Historically, this is supported among other things by the observation that the dawn of forested land conversion for agriculture heralded an expansion in prevalence of the disease in Africa (Laderman, 2002). Any attempt to restore natural forest ecosystems could thus be expected to impart some degree of control over the spread of the disease. The second row of Figure 25 highlights malaria-vector-related conditions that mangrove deforestation can initiate. Revegetation is conceptualised as a catalyst of the ecological restoration which instigates a reversal of these undesirable trends. In the case study region, the *Anopheles gambiae* complex of mosquitoes is the dominant malaria vector, with *A. melas* being most abundant in coastal lagoonal and mangrove swamps. According to Walsh et al, (1993), this anthropophilic *A. gambiae* complex has adapted to larval habitats facilitated by progressive deforestation, so that as these have become more available, there has been a commensurate upsurge in malaria incidence. A cocktail of ecologically rooted explanations has been propounded for this phenomenon.

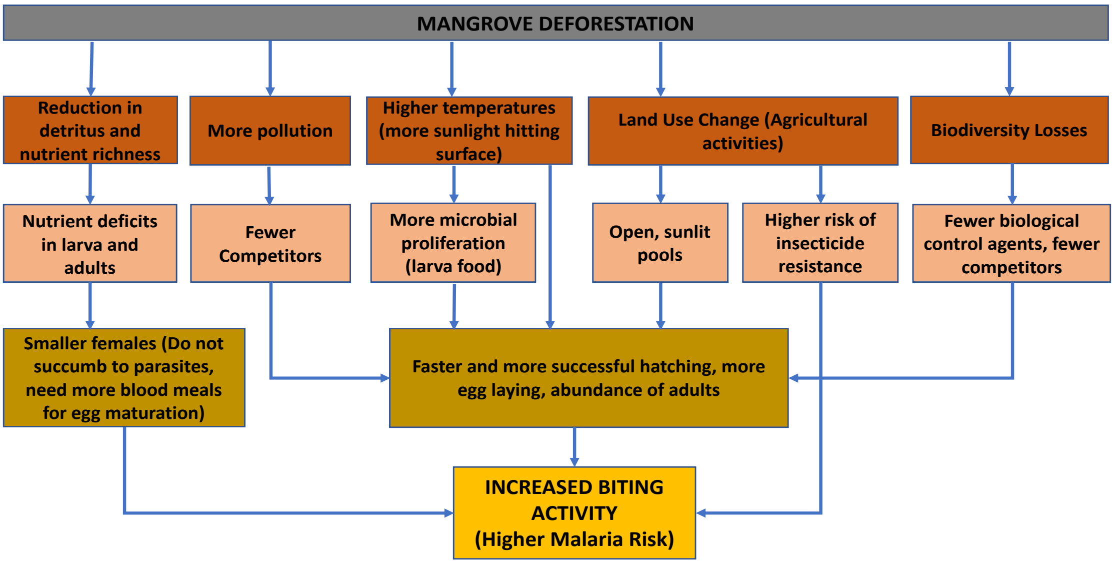

Figure 25: Potential pathways to changes in malaria vector abundance and behaviour in locales with deforested mangroves. Revegetation as an ecosystem intervention is conceptualised as a catalyst for the ecological restoration which instigates reversal of these trends.

5.1.2.2.1 Changes in Vector Behaviour

Vector behaviour is a noteworthy manifestation route of ecosystem effects on malaria endemicity, with links to the life cycle alterations that have bearings on the rate of spread of the culprit *Plasmodium spp* parasite. Well-functioning nutrient rich mangrove environments would be expected to yield larger and more parasite-competent female mosquitoes (Okech et al., 2007). Newly emerged mosquitoes under such conditions would thus be more likely to thrive for longer, thus increasing the possibility of transmitting the malaria parasite (Lyons et al., 2012). On the other hand, some other findings suggest that this may not always be the case. Takken et al., (1998) for example, demonstrate how lack of nutrient deficits in *Anopheles gambiae* emerging from nutrient rich habitats translates into delayed, less aggressive host-seeking behaviour. Thus, while resultant adult mosquitoes may be larger and more capable of transmitting the plasmodium parasite, their nutrient sufficiency diminishes the need for early blood meal nourishment for egg maturation in females. The need for blood meals through biting is curbed as a result, thereby limiting the risk of infection. Additionally, nutrient richness, while promoting parasitic competency in female Anopheles, also tends to limit life spans due to pathogenicity consequences on the mosquito itself. Lyimo and Koella, (1992) found that larger blood meals consumed by bigger females increases the possible number of plasmodium gametocytes they can ingest, which then raises the risk of them dying from the parasitic infection before they can transmit to humans. If the mosquitoes are unable to survive long enough to infect new hosts, then malaria infections in human populations would be controlled. Deemed beyond the scope of this study however, no mosquito sampling was conducted to comparatively investigate size, parasitic load, and biting aggressiveness for different mangrove conditions. Changes in vector behaviour, although considered to be relevant, are therefore excluded as an outcome-influencing condition in the causality analysis, primarily due to time and resource constraints.

5.1.2.2.2 Pollution

Within natural ecosystems, physico-chemical parameters related to ecosystem functioning have been shown to influence survival rates of both mosquito adult and offspring (Gimnig et al., 2001; Grillet, 2000). They include dissolved salts, organic and inorganic matter content, level of eutrophication, turbidity, mud content, vegetation cover, pH, dissolved oxygen, and light intensity. Such attributes fluctuate according to the extent of pollution arising from presence of solid and liquid wastes of anthropogenic origin. When mangrove restoration projects are undertaken, pollution tends to be limited, and the combined effects of reduced evapotranspiration, improved drainage and more frequent inundation gives rise to more favourable ecosystem functioning (Agyekumhene, 2019). A better-functioning mangrove ecosystem can therefore provide more favourable habitats for biodiversity, including predators of all mosquito life cycle forms, and those that compete with them for resources. Mangrove pollution was therefore deemed to be of causal significance and was an analysed ecosystem condition in the scrutiny of mosquito proliferation effects on malaria transmission incidence.

5.1.2.2.3 Land Use Change

Deforestation-related land use change, which makes room for more sunlight penetration and thus increases in ambient temperatures, creates more suitable habitats for vector mosquito breeding (Wolfarth et al., 2013; Marwato and Arbani, 1991; Ooi, 1959). This happens via a variety of mechanisms. Higher temperatures reduce incubation periods for larval hatching, as well as increasing rates of egg laying and biting

(Reiter, 2008). An increase in temperature also shortens the maturation time for adult *Anopheles spp* by decreasing the hatching-to-pupation time (Barreaux et al., 2018). Temperatures above 34°C can however delay larval development and trigger larval mortality, with survival beyond 35 °C being rare (Bayoh and Lindsay, 2003; Bhuju et al., 2018; Swain et al., 2008). Juvenile forms that often reside in small, isolated sunlit pools do not have the ability to escape heat-stressed environments on time, leading to mortality due to accelerated metabolic rates and rapid energy and/or resource exhaustion (Pörtner et al., 2017). According to (Dodson et al., 2012) higher temperatures lead to small larva sizes in *Anopheles, accompanied* by a matching decrease in flight range, thus limiting possible geographical reach of vector activity within an area.

Insecticide resistance has also been linked to rising temperatures associated with land conversion for agricultural purposes, with exacerbated mosquito enzyme activity being implicated in the resultant increase in insecticide detoxification (Matzrafi, 2019). However, Amarasekare and Edelson (2004) point out that the intensity of this link is influenced by several factors including method of application, quantity, and mode of application of the insecticide, among others. Further, where chemical intensive agriculture introduces pyrethroids into previously natural ecosystems, insecticide resistance becomes a challenge, especially in areas such as Ghana where ITN and IRS control programs employ pyrethroid-based insecticides. This was demonstrated by Diabate et al., (2002) and more recently by Ranson and Lissenden (2016) in respect of the *Anopheles gambiae* complex in similar locations.

The typical extrinsic incubation period for malaria parasites (Plasmodium spp) in mosquitoes is about 10 days, after which any subsequent blood meal could be a route to disease transmission to the human host (Rajatileka et al., 2011). Female mosquitoes must thus necessarily live beyond this period to be effective disease vectors. For female mosquito bites to result in malaria, an initial blood meal must contain plasmodium parasites which are incubated in the mosquito vector before re-transmission via a subsequent blood meal. Under rising temperature conditions blood meals are digested faster, so that further biting activity might be necessitated sooner, including a ratedoubling effect in some species of *Anopheles* mosquito (Afrane et al., 2012). Because blood meals are required for egg maturation (Shaw et al., 2020), additional biting maximises the chances of egg production and oviposition, with an associated expansion in mosquito population size and malaria transmission capacity. As environmental temperatures decrease, time required for malaria parasite development in the mosquito increases, with a significant jump from 12 to 30 days being observed for a temperature reduction from 25°C-20°C (Stresman, 2010). In other words, cooler temperatures, while being more conducive for minimising adult mortality rates (Christiansen-Jucht et al., 2014), may not necessarily lead to greater disease risk, given the inhibitory effects on parasite maturation and thus disease competence in the mosquito. Conversely, temperature ascents make it possible for parasite maturation to occur within a shorter period, creating greater opportunity for transmission to a host during a blood meal. Coupled with this reduced parasite incubation period, a temperature-influenced higher biting rate occasioned by a faster blood meal digestion, could facilitate a higher parasite transmission rate.

Ambient temperature change, as a direct consequence of mangrove deforestation and reforestation, and as an indirect impact of land use change, is consequently considered in this study as diagnostic predictors of malaria-related states of human health.

5.1.2.2.4 Vector Population Control

Vector control is a key avenue that has been exploited for malaria control because of the intractable connections between mosquito life cycles and transmission of the *Plasmodium* parasite. In Ghana infection prevention is one of the priority areas of the malaria control program, with specific objectives of ITNs being made available to 100% of households, and use of same by at least 80% of the population (Country Coordinating Mechanism, 2018). Emphasis has been placed on adult mosquito control, in the form of advocacy for and provision of insecticide sprays and creams, ITNs, IRS and to a much smaller degree, larvicide application (Letsa, 2021). Apart from such public health interventions, biological control mechanisms also exist, usually in the form of natural ecosystem processes that minimise insect populations. As previously highlighted, an extensive vegetation cover, as would be observed in undisturbed mangrove ecosystems, would inhibit the availability of sunlit stagnant pools that have been shown to be supportive of *Anopheles* populations (Shililu et al., 2003b; Munga et al., 2005), thus, serving as a control mechanism. One way in which this control is exerted is through suppression of optimal temperatures required for larva-nourishing microbial proliferation. As interpreted by Rao (Rao, 1984), this leads to larval growth delays that increase predation risk, thereby contributing to control of adult populations. Furthermore, chemical, and biological characteristics of well-functioning ecosystems have been shown to influence oviposition activities of gravid female mosquitoes. Aquatic zones associated with undisturbed ecosystems tend to harbour a diverse array of competing insects and their larvae, as well as fisheries which act as larval predators of mosquitoes. Such environments, which are also likely to be promoted by ecosystem restoration, have been revealed to be actively avoided by gravid female mosquitoes for oviposition purposes (Piyaratne et al., 2005; Kramer and Garcia, 1989; Muturi et al., 2008). This highlights a link between presence of biological control agents and potential proliferation of malaria vectors. Observation of abundance of potential biological control agents like fish is thus retained as a condition that potentially impinges on malaria incidence and is consequently included in the causality analysis.

5.1.2.3 Malaria (Personal) Preventive Measures

Use of personal protective measures against mosquito bites, particularly use of Insecticide treated nets (ITNs) at bedtime, is investigated as an additional causal condition in this study. This is because although IRS has been found to be more effective than ITNs especially for preventing infection particularly in under-5-year-olds in the country (Afoakwah et al., 2018), the latter remains the principal and most effective malaria control intervention in southern Ghana (Letsa, 2021). Widespread distribution of ITNs was initially adopted by Africa Heads of States as the most feasible strategy to attain the targets of a 2000 ‘Roll Back Malaria’ control program (Adjei and Gyimah, 2012), leading to both government and private sector investments in ITN provision for the poorest households (Awine et al., 2017). In a study conducted in the Volta Region by Nyavor et al. (2017), ownership and use of ITNs was found to be 81.3% and 66.4% respectively among respondents, with nearly 97.8% believing that same effectively prevents malaria infection. This perception aligns with the WHO (2021) submission that a statistical link exists between the use of ITN one hand, and reduction in both malaria infection and severity on the other.

5.2 RESEARCH METHODS

This study relies on a mix of qualitative and quantitative primary and secondary data collected via the 4 main processes illustrated in Figure 26, which were undertaken to address the research questions. Primary data comprised results from assisted health questionnaires and direct field observations regarding ecosystem states, whereas secondary data comprised confirmed hospital malaria cases.

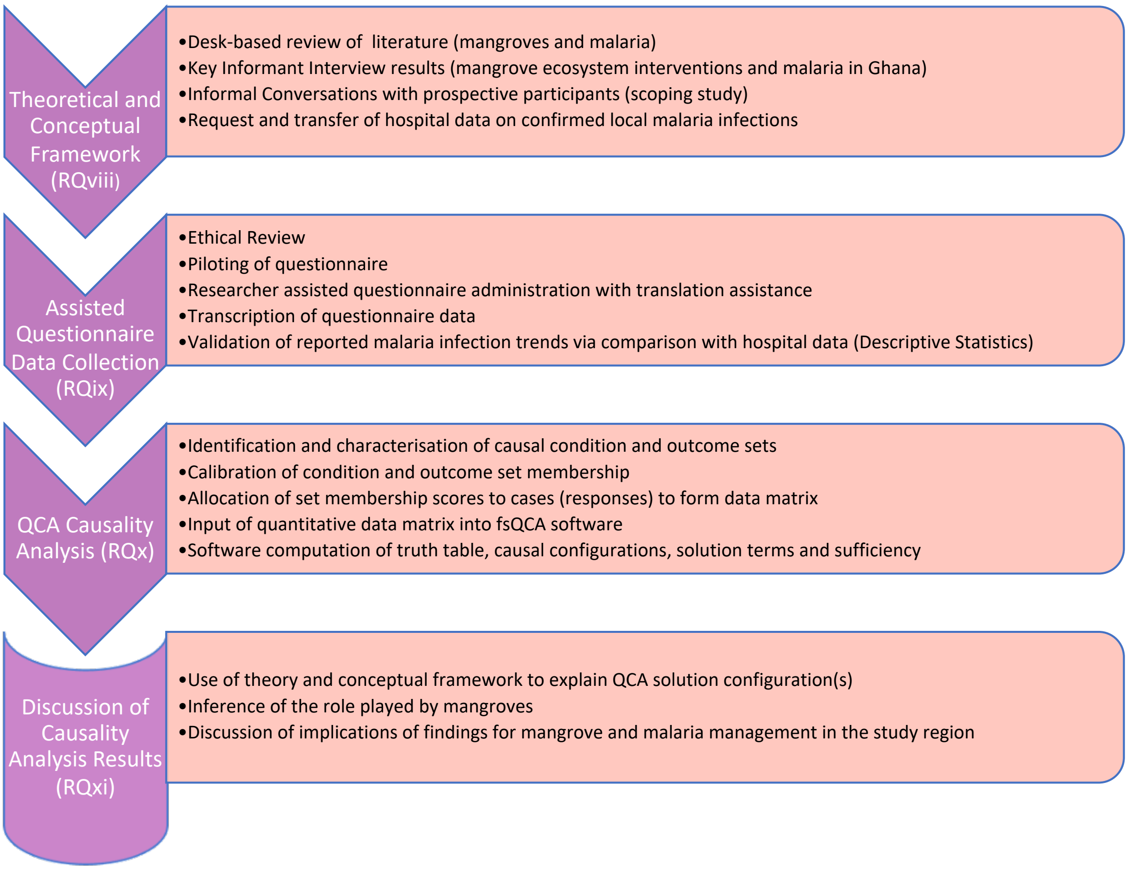

Figure 26: Methodological flow diagram indicating four main steps for addressing the research questions and the actions taken under each.

5.2.1 DESCRIPTION OF STUDY SITES

The west African state of Ghana lies along the Gulf of Guinea of the Atlantic Ocean. With an area of approximately 239,00km^2, the coastline stretches for approximately 550km, making up 6.5% of total land area. Over 90 lagoons are dotted along the coastal regions, with 4 major rivers draining the area. Of these rivers, the Volta is the largest, with its basin covering an approximate area of 400,00km^2 over six countries in the West African sub region (Bojang and Ndeso-Atanga, 2009), and tapering towards its estuary on the eastern coast of Ghana. This end point provides a suitable habitat for mangrove vegetation on the banks of the river and within its basin, as well as around the territories of the Songor and the Keta Lagoons (Spalding et al., 2010). These mangroves constitute the focus area of this research, and they fall within the Ada East and Anloga geographical districts found inside two Ramsar sites of the Greater Accra and Volta Regions of the country, respectively.

5.2.1.1 Songor Wetland

Listed in 1992, the Songor Ramsar site number 566 is the second largest in Ghana, and is situated within the Ada East District, 79km from the capital Accra. With an estimated area of 28, 740.4 hectares, it lies within the co-ordinates 05°45’N 00°30’E (Ramsar, 1998b). It provides the only natural entry point of the Volta River into the Atlantic Ocean, along with a closed lagoon, islands, flood plains, inundated mudflats, and sandy beaches. A coastal savannah of scattered shrubbery, saltmarshes, waterlogged grassland, and degraded patches of red and black mangroves characterise the habitats in this location. Streams and creeks are seasonal, necessitating digging of ponds for irrigation and livestock production purposes in drier seasons, although high salinity levels limit groundwater usefulness for domestic purposes (Ada East District, 2006). Since the location serves as a spawning site for fisheries, these habitats also serve as feeding and nesting grounds for a variety of species of tern, egret, avocet, and sea turtles and other IUCN Red List species (Ramsar, 2015b; Armah and Amlalo, 1998). Rainfall peaks in June and August-September, averaging at about 1600mm annually (Bojang and Ndeso-Atanga, 2009). Salt mining, fishing, and farming are the dominant occupations, with tourism fast becoming a key economic activity due to advancement of environmental conservation activities. Cultivated crops include maize, okra, tomatoes etc, with small-scale livestock farming of pig, chicken, goat, and duck. Blocked creeks, over-fishing, over grazing and excessive mangrove exploitation are the major ecological threats in the area (Ramsar, 1998b). Land is owned via kinship of groups and families of the native Ningo people, whose elders oversee allocation and use. Two of the case study communities (Azizanya and Obane) are found here, in the Ada East district, and were selected based on the existence of mangroves and/or mangrove restoration strategies.

AZIZANYA: The community is found at the southernmost tip of the district, on the western bank of the Volta estuary. It is a fishing village consisting mainly of male fishers and female fishmongers who sell their produce to near and wider communities. The mangroves in Azizanya have not seen and intentional, large-scale reforestation, and the ecosystem is degraded due to extensive exploitation (Figure 27). Mangrove use is thus not as widespread today as it used to be, so perspectives are from people currently not benefiting from the impacts of healthy or restored mangroves.

Figure 27: The mangroves of Azizanya were patchy and significantly degraded, leading to extensive loss in cover.

OBANE: This community is located 10.2km north-west of the Songor lagoon and provides a suitable habitat for birds. Adjacent to the Luhue creek that branches from the Volta River, this community was selected for its mangrove revegetation between 1993 and 1999 by the Wildlife division (Figure 28). With landowner and community support, the project was aimed at restoring mangroves degraded through land use conversion for rice and sugarcane farming. Exploitation of the restored mangroves has been restricted by by-laws which have largely been respected by the collaborative community (Derkyi, 2007). This site was selected for the unique opportunity to sample perspectives of people who have experienced the benefits of ecosystem restoration in the form of mangrove revegetation.

Figure 28: The Obane mangrove restoration project involved drainage optimisation and mangrove revegetation, backed by institution of mangrove use regulations.

5.2.1.2 Keta Lagoon Complex

The Keta Lagoon Complex Ramsar site of the Volta Region is found on the eastern corridor of the Volta River and consists of an open lagoon with brackish and freshwater influxes bordering islands and coastal strips of land. Covering an area of 38,110.86 hectares between co-ordinates 05°55’ N 00°50’E, it was designated as a protected Ramsar Wetland number 567 in 1991 (Ramsar, 1998a). The dominant vegetation type is grass, but swamps, scrublands, and heavily exploited mangrove forests constitute the other vegetation types. The presence of the Tordzi and Volta rivers makes water a permanent feature. It serves as a crucial wetland habitat for a variety of species, notable among which are endangered manatees, sea turtles and migratory bird species (Ramsar, 2015a). Land is owned and used by family kinship, with chiefs, clan and family heads being the custodians of all resources therein. Sea erosion, pollution and over exploitation of mangrove wood are the major wetland-related concerns in the region. As a result, ecological restoration and species monitoring are important part of the protection and conservation activities of the Wildlife Division in this locality. About four out of ten persons engage in skilled agricultural, forestry or fisheries occupation, with the remainder taking up service, sales and craftmanship job types. Agricultural land use is predominantly for crop and livestock (mostly poultry) farming, but tree planting and fish farming are also present (Ghana Statistical Service, 2014). Anloga, which was formerly part of the larger Keta district until 2019, is one of the districts within this Ramsar site, where three of the study sites are found (Anyanui, Tunu and Salo).

ANYANUI: This community is a mangrove farming community on the eastern coast of the Volta estuary. The people comprise a sizeable number of fishers and/or mangrove farmers many of whom apply a well-managed community-initiated mangrove reforestation regime, involving replanting harvested mangrove wood. There is a mangrove market present (Figure 29), where people from neighbouring communities come to purchase mangrove wood for different purposes. It also serves as a port for canoe/boat transportation or people and goods from inner island communities, as well as for tourism and recreational activities. This location has the most abundant and mature-looking mangrove vegetation (Figure 30) and was selected to sample views from people living near healthy mangroves.

Figure 29: Bundles of harvested mangrove wood displayed for sale at the Anyanui port. Mangrove forest is visible in the background, along with a tourist boat and canoes for transporting people and goods to and from nearby islands.

Figure 30: Anyanui had the most abundant, healthiest-looking and best-managed mangroves among the study sites.

TUNU: This village is a smaller neighbour to Anyanui, also made up of fishers and people with keen interests in diverse mangrove farming. Fewer people own mangrove land, but those that do tend to preserve it to maximise fisheries benefits. Periwinkle harvesting is popular in this locality, and the mangroves are not degraded (Figure 31). Thus, like Anyanui this community was selected to represent views from people living near healthy mangroves.

Figure 31: Tunu is a smaller village next door to Anyanui and has healthy mangroves closer to the settlement.

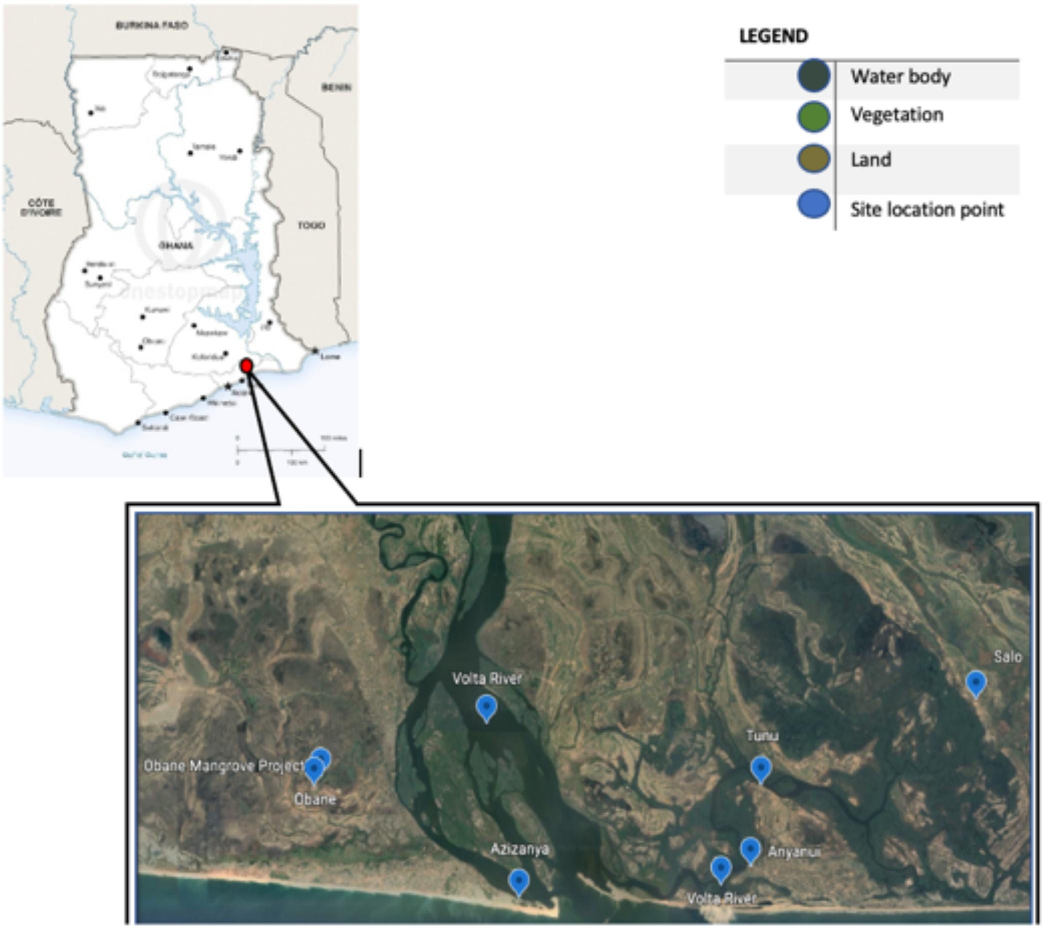

Figure 32: Map of study locations close to the Volta estuary

SALO: This is a non-mangrove community that engages mostly in farming and petty trading. It was selected as a 'control' community to represent analogous perspectives about malaria, but in this case from people who do not live close to mangroves. It is located 9.90km north-east of the Anyanui entry point of the Volta River (Figure 32).

5.2.2 DATA COLLECTION

5.2.2.1 Health Questionnaires

In August 2019, a scoping study was conducted in the case study location to identify mangrove communities with the characteristics of interest. Informal conversations were had with opinion leaders (e.g., village chiefs, chief fishers) and households to collect background information about mangrove use and revegetation impacts, as well as willingness to be part of the research. Personnel of the local offices of the Wildlife Division were also formally invited to proffer some insights into mangrove conservation, after which two of their field rangers were recruited to help with the translation tasks for the research exercise (See Appendices K and L for approval letters). The inclusion of the rangers fostered some trust because local people are familiar with the staff, having often been involved in similar participatory research conducted in the area.

The assisted health questionnaires (copy attached as Appendix M) were crafted in English and verbally translated into local dialects (Dangbe for Azizanya and Obane; Eve for Anyanui, Tunu and Salo). Prior to the health survey, key informant interviews about mangroves and general links to human health in Ghana were conducted in March and April 2021 (See Appendices D and E for interview guides). During that exercise, informants from the academic, conservation and public health sector among others were interviewed for viewpoints on state and use of mangrove ecosystems, and about malaria prevalence and management in Ghana. The insights captured thereof were integrated into the community and participant selection criteria, design, and specific questions of the health survey questionnaire. The final questionnaire was approved by the FST (Faculty of Science and Technology) Research Ethics Committee of Lancaster University and was designed using the Ghana Health Service household malaria survey questionnaires as a guide (Ghana Statistical Service, 2011). The questions were tested for sensitivity, especially around socio-economic themes, to circumvent any exceptional ethical issues. The questionnaire was piloted in Ghana during the first phase of fieldwork, to provide the right atmosphere and context for testing both language clarity, nature of potential responses and general reception, before being fully administered.

Based on the information gathered during the preparatory stages, the questionnaire was designed to include three main groups of questions:

1. Personal and residency information
2. Mangrove state and use where applicable.
3. Malaria experiences over time.

After verbal translation of participant information and consent sheet information (Appendices A and B) for each respondent, it was explained to participants that their consent was being given by virtue of voluntarily agreeing to answer the questions.

Questionnaire responses were collected anonymously and in multiple answer formats to enable easy manipulation for software analysis. These formats consisted of multiple choice, short statements and Likert-style estimates particularly about changes in malaria incidence. Thirty questionnaires were administered by the researchers per community, over a period of approximately three weeks in August 2021, resulting in a total of 150 questionnaires being completed for the 5 sampling sites.

Sampling was purposeful, with a conscious effort to gather accounts from long-term residents who were at least 30 years old and who could therefore be invited to engage in a recall exercise spanning several years. People who were older than 80 years old were excluded, to avoid risk of inaccurate responses arising from age-related memory decline. Both men and women were included in the survey, but more women were targeted than men, as they tend to be the primary caregivers in households and are thus more likely to know about past bouts of illness.

5.2.2.2 Hospital Data

As part of the monitoring and evaluation process for the National Malaria Control Programme, the Ghana Health Service collects data on reported malaria cases for all its district hospitals. District level data were obtained from the Ghana Health Service. In line with the normal procedure for this institution, appropriate data request documentation was submitted and approved (See Appendices G, H, I and J). The designated information was electronically transferred to the researcher, and then stored in encrypted form on a password-protected computer. Data selected and used for this study consisted of collated verified cases of malaria reported at the district hospitals relevant to the case study sites. The data requested were in anonymized form, filtered only for residents of the sampling location and dating as far back as possible, based on availability. Other demographic information captured in the data relates to patient age and occupation.

5.2.3 DATA PROCESSING

'Causal inferences' are part of techniques that estimate the impacts of events and interventions by leveraging theoretic knowledge about them. In answering questions about research problems or outcomes, reliance on observational data is not as popular in this research field as the use of randomized controlled experimental methods (Brady, 2008; George and Bennett, 2005; Morgan and Winship, 2015). However, as highlighted by Pearl (2010), causal inference frameworks can be used in lieu of randomized experiments to draw reliable conclusions about observational data, which are particularly be useful in circumstances where experiments are not feasible. There are two major challenges associated with observational studies. One of these is the problem of selection bias, where chosen research participants supply information that does not necessarily reflect overall population characteristics. The other challenge is referred to as 'confounding bias', in which the effects of an intervention factor is complicated by associated concomitant interventions or baseline characteristics which may not exert any causal effects (Lu, 2009). One of the methods developed to overcome the weaknesses of observational data is Directed Acyclic Graphs (DAGs). These graphs visualise and quantify causal relationships by making broad qualitative assumptions about how a system is operating, leading to deductions about population outcomes. The associated assumptions need to be grounded in theory and justifiable by domain knowledge.

A DAG framework that has gained progressive use by ecologists is Structural Causal Modelling (SCM) (Grace and Irvine, 2020; Cronin and Schoolmaster Jr, 2018). SCM utilises prevailing knowledge about system relationships to inform statistical adjustments aimed at eliminating confounding bias. It has been applied across various other disciplines, including epidemiology (Pearce and Lawlor, 2016), paediatrics (Williams et al., 2018), and psychology (Rohrer, 2018). Set theoretic approaches, which are based instead on case membership in condition sets, have also been used to arrive at causal inferences about interventions and events. A typical example is Mill's methods or set theory based historical explanations (Mahoney et al., 2009) which do not use 'truth tables'. Qualitative Comparative Analysis (QCA) is another set-theoretic approach, but it relies on truth tables and a logical minimisation step, presenting a parsimonious expression of logical explanations for an outcome. This a unique and formal feature of QCA, which other set theoretic approaches lack (George and Bennett, 2005). For the current study, QCA is chosen because theoretical reasons exist for the assumptions made in framing the research questions, and in designing the data collection framework. These reasons serve as bases for assignment of cases to sets of conditions that potentially give rise to the outcomes observed in participant responses.

5.2.3.1 Why Use QCA?

Whereas a typical case study involves detailed interpretations from deep familiarity with one or few cases, the variable-oriented approach relies on larger sample sizes to validate generalizations at the expense of case information depth. The key advantage of systematic cross-case comparison offered via variable-oriented approaches like regression analysis, is often eroded by the lack of confidence in the type of causal relationships that can be generated. In contrast to the unique strength of case studies where causality can be justified with intimate, real-life case knowledge, causality in variable-oriented techniques may not necessarily match with reality. QCA avoids that trade-off between causality that is grounded only on case attributes and variable dependent causality, by making room for analysis of complex, generalizable causality (Schneider and Wagemann, 2012). As a result, QCA allows for valid, systematic cross-case comparisons. The method has been used in a wide variety of research fields, including public health (Warren et al., 2014; Hanckel et al., 2021), public administration (Thomann and Ege, 2020), project management (Ma and Fu, 2020), business management (Berger, 2016) and conservation management (Arts and De Koning, 2017)

The QCA method helps to make sense of complex causality relationships (Rihoux and Ragin, 2008) by assessing the following situations that are not easily interpreted by the predictor 'net effects' target associated with conventional regression analysis:

- How conditions work together to give rise to an outcome, instead of individually (Conjunctural causality)
- How more than one condition or combination(s) of conditions might lead to the same observed outcomes (Equifinality). Recognising that a condition is sufficient implies that there are other conditions or combinations of conditions that also elicit the outcome of interest.

- How a condition works differently from one case to the next in eliciting outcomes (Asymmetry), so that the explanation for non-occurrence of an outcome cannot be simply derived by negating that for the occurrence of that same outcome.

5.2.3.2 The QCA Process

Using established or dominant theoretical principles pertaining to the phenomena under investigation as a guide, the research design for QCA analysis first involves familiarisation with case characteristics. This is followed by researcher determination of conditions that are relevant and therefore of causal value in the dynamics that lead to a particular outcome (Arts and De Koning, 2017). These conditions then serve as anchor points for the examination of the catalogued case characteristics, under the minimum assumption that the observations could be explained using the best available knowledge about the most likely causal factors and how they interrelate. Data analysis is conducted with a software (in this case fsQCA), which uses a combination of fuzzy set theory complemented by Boolean minimisation, to determine which conditions (or combinations of same) work together to elicit the outcome of concern (Rihoux and Ragin, 2008). After settling on conditions, a data matrix is created, which collates the degree to which cases belong to the set of the main causal conditions identified; and, based on the expression or otherwise of an outcome. A case that exhibits characteristics of a potential causal condition can for instance be given a score of 1 for that condition, whereas those that do not are scored 'zero' in the data matrix. After this data matrix has been uploaded into the software, algorithms are used to investigate relationships between sets of cases that share common combinations of conditions. The result of this computation is a so called 'Truth Table', which displays how often logically possible combinations of conditions occur, and what the observed outcome is when they do. A solution term(s) is also generated, to illustrate the various conditions or combinations of conditions working together most consistently in the causal structure of the system under study. This solution highlights the conditions which are necessary and sufficient for the observed outcome, paving the way for theory-informed interpretation of causal relationships.

The latter steps of analysis of necessary and sufficient conditions can be refined via an iterative process of returning to case and condition selection, as well as calibration, steps to make changes (Figure 33). Such adjustment could be in the form of case exclusion or recalibration that can help to eliminate contradictory and redundant relationships.

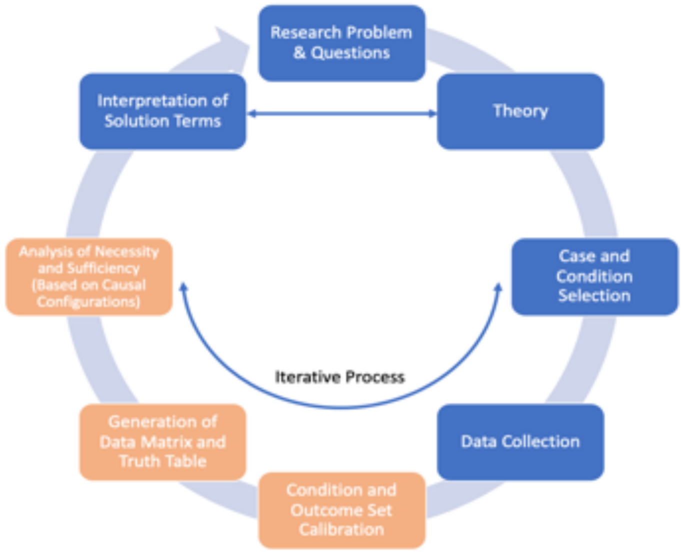

Figure 33: Cycle of the QCA Research Process. Actions coloured orange are conducted with QCA software.

5.2.3.3 Case Context

Having been designed to investigate diversity, it is important in QCA for the intended dataset to include cases where the outcome of concern is both present and absent. In this regard, the criterion is met because the data in this study points to a diverse nature of malaria experiences over time. In other words, different extents of both malaria incidence reduction and increase are reported. In this micro level QCA research, the outcome of interest is the 'reduction in malaria infections with time' (RMI), as theorised from the conceptual framework. This expected outcome is being investigated from the perspectives of people living in mangrove communities, and in respect of conditions occasioned by mangrove ecosystem interventions (Table 3). However, the QCA process offers the advantage of including conditions generated by other non-mangrove interventions for analysis (such as use of ITNs), in conjunction with mangrove-related ones. All cases are similar in this respect, in addition to similarities in other demographic characteristic like nature of livelihoods and age groupings etc (Table 14). Thus, these similarities demarcate a limited region of homogeneity within which cases may vary. Heterogeneity is guaranteed by the fact that not all cases belong to the selected sets of causal conditions (mix of restored, degraded, and non-mangrove communities), nor do they exhibit the same degree of the expected outcome, making analysis of asymmetry possible. The conditions in Table 14 were selected for causality analysis based on public health malaria policy interventions, as well as knowledge on potential malaria-influencing consequences of ecological interventions in mangrove ecosystems in the relevant locations.

A purposeful sampling strategy ensured that cases were similar enough to compare. Only respondents who have lived for an extended period in mangrove communities (at least 10yrs), who can correctly identify malaria symptoms and who additionally have a recollection of household infections with the disease were included in this analysis. Each questionnaire response constituted one case, so that there are 30 cases per community. The conditions described in Table 14 were identified as being relevant to the outcome in this context, being careful to consider relevant key ecological underpinnings suggested in the conceptual framework. They constitute the 'condition sets' to which cases are allocated based on the nature of questionnaire responses, in addition to the RMI 'outcome set.'

Table 14: Description of Causal Conditions Investigated in relation to the Outcome 'reduction in malaria infections with time'.

CONDITION	RESPONSE INDICATOR	JUSTIFICATION
REDUCED AMBIENT TEMPERATURE (RAT)	Identification of changes in coverage of mangrove vegetation/tree canopy	Thicker vegetation reduces the amount of direct sunlight hitting the ground or water, which is thought to reduce mosquito breeding rates
IMPROVED WATER QUALITY (IWQ)	Identification of zero pollution characteristics	Greater pollution levels aggravate *Anopheles spp*. mosquito proliferation
ARRESTED MANGROVE LAND CONVERSION (MLC)	Absence of degraded mangroves, controlled land use change for other activities	Agricultural activity removes vegetation cover, deforestation interferes with ecosystem integrity/capacity for vector control
PRESENCE OF BIOLOGICAL CONTROL AGENTS (BCA)	Observation of greater fisheries numbers in mangrove environment	Adult and juvenile fisheries feed on and control the growth of mosquito eggs/larvae into adulthood
USE OF MALARIA PREVENTIVE METHODS (MPM)	Use of at least one verifiable method of preventing mosquito bites (E.g., use of insecticide treated sleeping nets)	Malaria infections are transmitted only through the bites of infected female *Anopheles* mosquitoes.

5.2.3.3.1 Calibration of Set Membership

Cases (referring here to an individual respondent's perceptions regarding the specific research scenario) are measured according to how they fit within the boundaries of literature-sourced ecosystem condition sets that are relevant to malaria outcomes, based on Mahoney (2010). In 'crisp set' QCA, a case is assigned a membership score of 1 if it exhibits characteristics of a condition or outcome set, and 0 if it does not. While aspects of responses in this study can be dichotomised into binary (crisp) set membership, others cannot. For example, participant responses to the question of whether a malaria preventive measure has been used would either be a 'yes' or a 'no', making crisp set membership scores possible. On the other hand, participants' malaria infection experiences, which is investigated as an outcome in this study, is based on often imprecise participant recollection of past disease episodes within their households. The lack of verifiable conceptual boundaries in such recall exercises makes it difficult to apply crisp calibrations to responses about the outcome. Fuzzy set QCA is therefore adopted in this study overall, being cognizant of the fact that crisp set calibration, which is merely a more precise form of fuzzy set, can still be applied to the aspects of the data that lend themselves to it.

For the creation of the data matrix, calibration for causal conditions was dichotomous. Cases that clearly exhibit condition characteristics are awarded set membership scores of 1, whereas those that do not are given a score of zero. For analytical reasons, Schneider and Wagemann (2012) advise against the allocation of set membership score of 0.5, which is the point of maximum ambiguity about a case's membership of a condition or outcome set. This is because calibrating fuzzy sets based on statistical measures like mean and median (0.5 is the median for a 0 to 1 interval) means that the properties of the data are being relied upon in place of the concept being investigated. This increases the possibility of invalidation of the calibration framework in the event of any alteration of data characteristics, such as the exclusion of addition of cases during iterative stages of the QCA analysis. Moreover, a set membership scores of 0.5

translates into the weakest possible conceptual statement about the case with respect to a condition or outcome, and consequently such cases are not represented in any row in the ensuing truth table. Such 'ambiguous' condition set membership allocations were thus avoided.

Calibration of outcome set membership for this study (Figure 34) was thus based on factors that are external to the data, relying instead on integral definitions peculiar to this research. For example, where a case reports no perspective on changes in malaria incidence over time, set membership of the outcome set is deduced from an extra metric – the last malaria episode recollected. If no incident has been recalled in the last year, it is qualitatively assumed to be demonstrative of at least a moderate reduction in malaria incidence. Because a Likert-style scale was used to estimate changes in malaria incidence, a dichotomous key was not used for calibrating membership of the outcome set. The survey statement for the outcome set was "malaria Incidence has subsided over the past few years", and respondents were asked if they agree with this statement. The answer options were 'significant decrease', 'moderate decrease', 'no change', 'moderate increase', and 'significant increase' in infections. Respondents reporting a significant decrease in malaria incidence strongly agree with the survey statement and are given a full outcome set membership score of 1, while those who report only a moderate decrease are scored 0.8, as they only agree 'somewhat' with the statement. On the other hand, all cases that report either a significant or moderate increase in malaria incidence are deemed to be fully out of the outcome set. This is because by reporting an increase rather than a decrease in infections, they are essentially disagreeing with the survey statement, and are thus assigned a membership score of zero. Finally, respondents who recall 'no change' in incidence, although in partial agreement with the statement, exhibit weightier disagreement with the statement; their state of relative indifference signifying that they do not agree with the survey statement. However, because those respondents deliberately declined to explicitly disagree with the survey statement, the cases are assigned an outcome set membership score of 0.2, indicating that they 'disagree somewhat' with the statement.

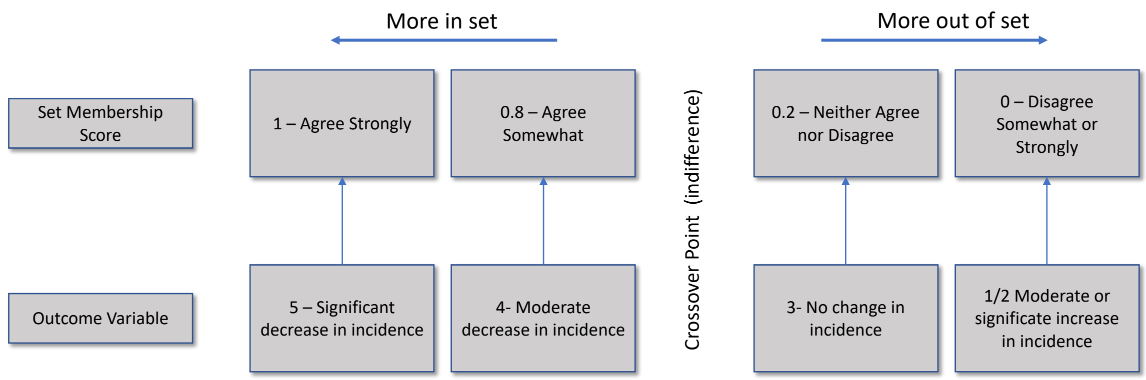

Figure 34: Calibration Framework of Outcome Set Membership (modelled after Emmenegger et al., (2014), which allows for both differences in degree and kind of response to be captured in fuzzy sets. Thus, qualitative dimensions of perspectives expressed in survey responses are not lost.

5.2.3.4 Description of Measured QCA Parameters

In fuzzy set QCA, set theoretic subset and superset relations and Boolean algebra algorithms in the fsQCA software analyse how the causal factors (conditions) combine to give rise to the observed phenomenon (outcome). In other words, the eventual solution terms produced disclose which conditions are present or absent whenever the outcome is observed, and additionally highlight which conditions or combinations of same, are 'necessary' or 'sufficient' for the outcome. The logically achievable condition configurations associated with the outcome variable are listed in the 'truth table', including both configurations for which cases can be empirically assigned, and those not demonstrated in any case. Thus, a truth table allows for analysis of diversity, in terms of which configurations are most populated by cases, and which ones seldom occur in the observed scenarios.

Rows in a truth table lists all the 2^k potential combinations of causal conditions (where 'k' refers to the number of conditions), and the respective numbers of cases displaying those configurations in the data matrix. In the outcome column of the truth table, configurations for which the outcome is positive (observed) are given a score of 1 by the QCA software, whereas 0 is assigned for those where the outcome is negative (not observed). Cases displaying the same configuration of conditions, but different outcomes are 'contradictory', and those configurations that are displayed in none of the cases are the 'logical remainders.' Remainders occur because of the phenomenon of limited diversity of reality, so that even though a configuration is theoretically expected to lead to the outcome, that configuration-outcome relationship may not be reported in the data due to the limitations in nature of cases sampled from the population. These remainders can however be used to generate a more parsimonious solution (Seawright, 2014), under the assumption that said remainders would have been sufficient for the outcome if they had occurred.

In the truth table, sufficient conditions are those conditions which also exhibit the outcome anytime they occur. In other words, a condition (or combination of conditions) that is sufficient by itself is always observed along with the outcome in all the cases it, and never in its absence. This however does not mean that the absence of that condition is sufficient for the absence of the outcome, and no single sufficient condition(s) by itself can explain the outcome in full. A necessary condition(s) on the other hand is one that must be present for the outcome to be observed, so that the outcome is never observed in its absence. This means that while a necessary condition may occur without the outcome necessarily occurring, the outcome is never observed in the absence of a that condition. If at least one of the causal conditions is absent across all the truth table rows which are positive for the outcome, then no necessary conditions exist.

There are two software-generated parameters of fit in QCA analysis: consistency and coverage. To measure the cumulative subset relationship of a configurational structure for all associated cases, 'consistency' scores are generated by the QCA software. These scores convey they extent to which exhibition of a particular causal configuration consistently leads to the observation or otherwise of the outcome (Epstein et al., 2008). The consistency score ranges from 0 to 1, with 0 indicating that a subset relationship is absent. The closer the consistency is to 1, the more assuredly a causal configuration leads to the outcome. For 'small N' fuzzy set analysis, a researcher-set consistency threshold of at least 0.8 is acceptable for a solution term to be considered as causally significant. For a condition set X and an outcome set Y:

$$\boldsymbol{Consistency}\ (\boldsymbol{X_i} \leq \boldsymbol{Y_i}) = \sum[\boldsymbol{min}(\boldsymbol{X_i}, \boldsymbol{Y_i})]/\sum(\boldsymbol{X_i})$$

Secondly, the software-generated measure of 'coverage' signifies the proportion of cases covered by a particular causal expression, and thus indicates the degree to which the outcome is explained by a condition or a solution term. Similar in usefulness to the 'variance' measure in regression analysis, coverage gives an impression of the relative significance of a particular causal expression or solution term. Coverage values range from 0 to 1, and the smaller the coverage, the less strongly a solution can be considered in explanation of the outcome. For a condition set X and an outcome set Y:

$$\boldsymbol{Coverage}\ (\boldsymbol{X_i} \geq \boldsymbol{Y_i}) = \sum[\boldsymbol{min}(\boldsymbol{X_i}, \boldsymbol{Y_i})]/\sum(\boldsymbol{Y_i})$$

5.3 RESULTS AND DISCUSSION

In the first instance, highlights of the health survey are reported, revealing the differences and similarities in demographic and mangrove use characteristics of respondents from the different communities. This is done to demonstrate how the simultaneous heterogeneity and similarity criteria are met for the ensuing QCA process. This is followed by a basic aggregation of the participant-reported malaria incidence experiences over time, as compared to the hospital-reported figures of confirmed malaria cases in the respective districts where study sites are located. This step seeks to explore the validity of malaria incidence trends recounted by participants, being cognizant of the potential inaccuracies that may characterise retrospective recall exercises as employed in the survey. Finally, results of QCA analysis are presented and discussed within the context of the theory-supported mechanisms underlying the uncovered causal relationships between the conditions and outcome investigated.

5.3.1 Demographic Characteristics and Mangrove Use

The distribution by age, sex, education level and duration of domicile for respondents in each community is shown in Table 15. 87 females and 63 males were interviewed, more females having been consistently targeted across the locations in pursuance of their unique perspectives on family health as primary caregivers. The dominant age group of participants was 30-39 years making up nearly a third of the responses, with only 11 out of the 150 contributors being above the age of 70 years. People with primary school education formed 59% of participants sampled, followed by 30% with no formal education found mainly in Azizanya and Obane communities. No participant reported tertiary level education status, with the remaining 10% of respondents being secondary school leavers. Only 22 out of the 150 respondents had lived in these communities for less than twenty years.

Table 15: Characteristics of Research Participants

Community (30 respondents each)	**Sex: male (M)/female (F)**		**Age (Years)**					**Formal Education Level**				**Duration of Domicile (Years)**			
	M	F	30-39	40-49	50-59	60-69	70-79	Primary or Middle	Secondary	Tertiary	None	6 to 10	10 to 15	15 to 20	Over 20
ANYANUI (healthy mangroves)	12	18	10	4	7	6	3	22	4	0	4	1	2	2	25
AZIZANYA (degraded mangroves)	13	17	12	9	6	3	0	17	0	0	13	0	1	3	26
OBANE (restored mangroves)	12	18	9	7	6	5	3	14	4	0	12	1	0	4	25
SALO (no mangroves)	13	17	6	9	7	6	2	17	3	0	10	0	0	3	27
TUNU (healthy mangroves)	13	17	9	7	5	6	3	19	4	0	7	0	1	4	25
TOTAL (150)	63	87	46	36	31	26	11	89	15	0	46	2	4	16	128
Percentage	42.0	58.0	30.7	24.0	20.7	17.3	7.3	59.3	10.0	0.0	30.7	1.3	2.7	10.7	85.3

Although not all communities have mangroves (one community, Salo, did not and accounted for 30 of responses), and only 9 residents gave indications about mangrove land ownership and access, most people reported some degree of mangrove product use or benefit. Mangrove wood products are used either domestically (as firewood, roofing material, fishing baskets/stakes, etc), or commercially (for smoking fish, as construction input, sold on the market etc) (Figure 35). In Anyanui, which is a community with a strong mangrove farming culture, all the 6 interviewed mangrove landowners sell mangrove wood, which is patronised locally and by people in neighbouring communities. This was true for Tunu community as well, where the remaining 3 mangrove landowners attested to commercial sale of mangrove wood products as a livelihood venture. It is worth noting that presence of and access to mangrove land is not a pre-requisite for mangrove resource use or consumption, as goods can be purchased from markets and are not necessarily always locally sourced. Therefore, while some people physically interact with the mangrove forests (fishers, mangrove farmers, wood harvesters) others interact with and benefit from these mangroves indirectly. Related malaria experiences could thus arise from proximity to malaria vectors within the forests, or from any combination of mangrove goods, services or disservices that have bearings on malaria prevention, transmission, and treatment.

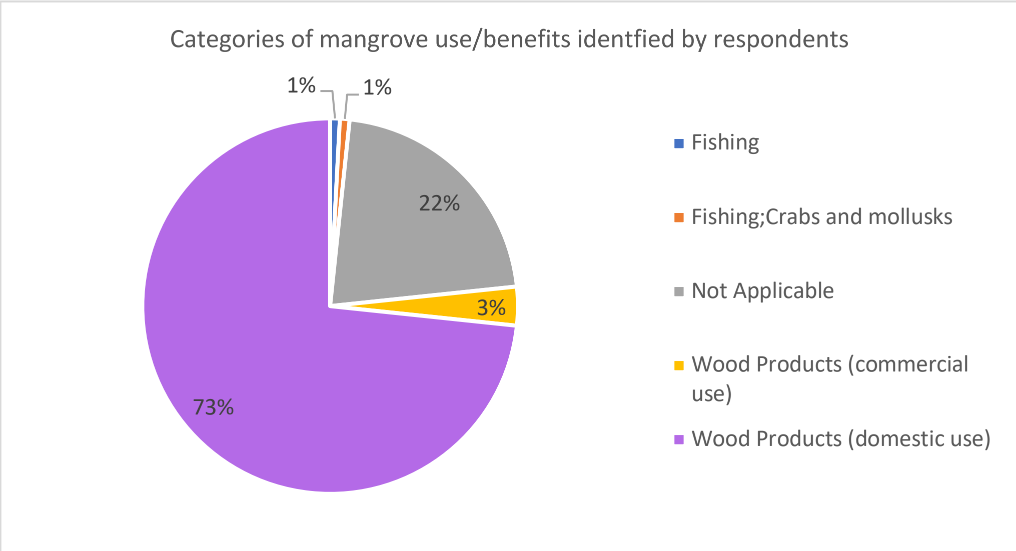

Figure 35: Main categories of mangrove use/benefits identified by respondents.

While 44 out of the 120 respondents of mangroves settlements mention using indigenous herbal medicine in malaria treatment and prophylaxis, mangrove-related flora does not feature as ingredients in any of those herbal preparations. The herb that was consistently cited as being useful in malarial fever treatment and prevention was the 'neem' tree *Azadirachta indica*, aqueous leaf and bark extracts of which have found longstanding use in Ghana for that purpose.

Apart from mangrove wood, other goods and benefits derived from the mangrove ecosystem include fisheries and molluscs, which are either sold on the market or consumed locally. Fishing is thus a major occupation in the mangrove communities except Obane, which harbours inland mangroves that tend to support only oysters. Other occupations cited are represented in Figure 36. In the mangrove communities, women were mostly fishmongers and small traders, whereas farming of food crops and mangroves along with fishing were the two main occupations of male respondents. Residents in Salo, the non-mangrove community, reported a more diverse array of livelihood activities, including carpentry masonry and dressmaking.

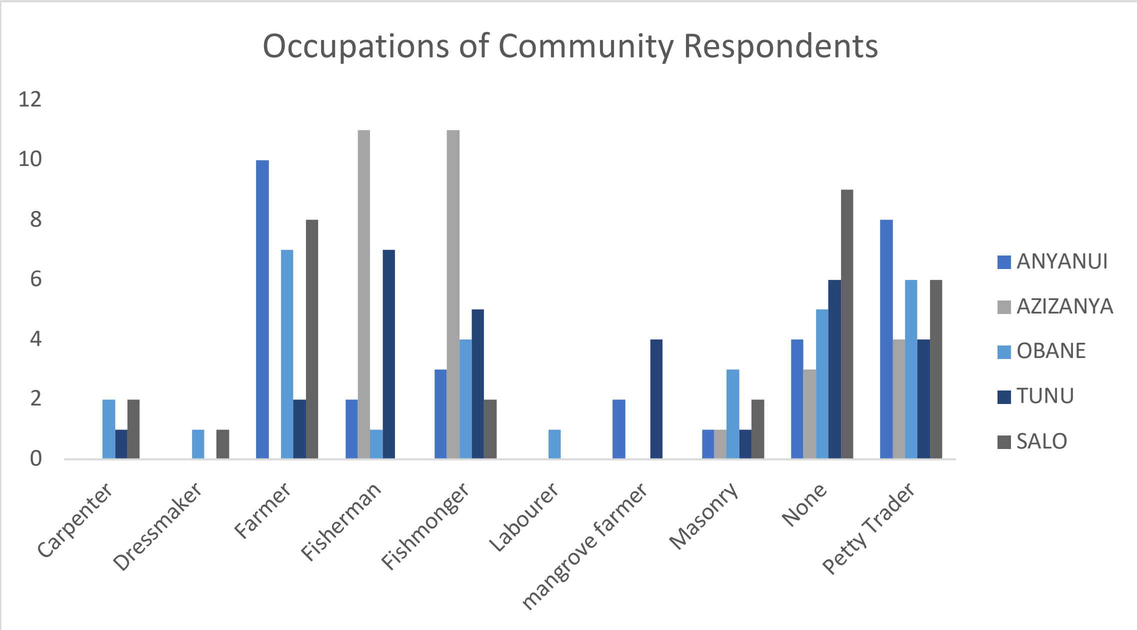

Figure 36: Occupations of Community Respondents

5.3.2 Malaria Knowledge, Preventive Measures and General Incidence Changes

People who accurately identified at least one symptom of malarial fever were the most likely to report having taken appropriate treatment actions, often involving over-the-counter antipyretic drugs or a visit to the clinic. Respondents who associated malaria with mosquito bites also tended to be those who indicated regular household use of at least one personal protective measure against mosquitoes (Figure 37). For households where protective measures are mentioned, they are usually in the form of use of ITNs, mosquito coils or insect repellent creams; and these interventions are undertaken by all household members in most of the relevant cases.

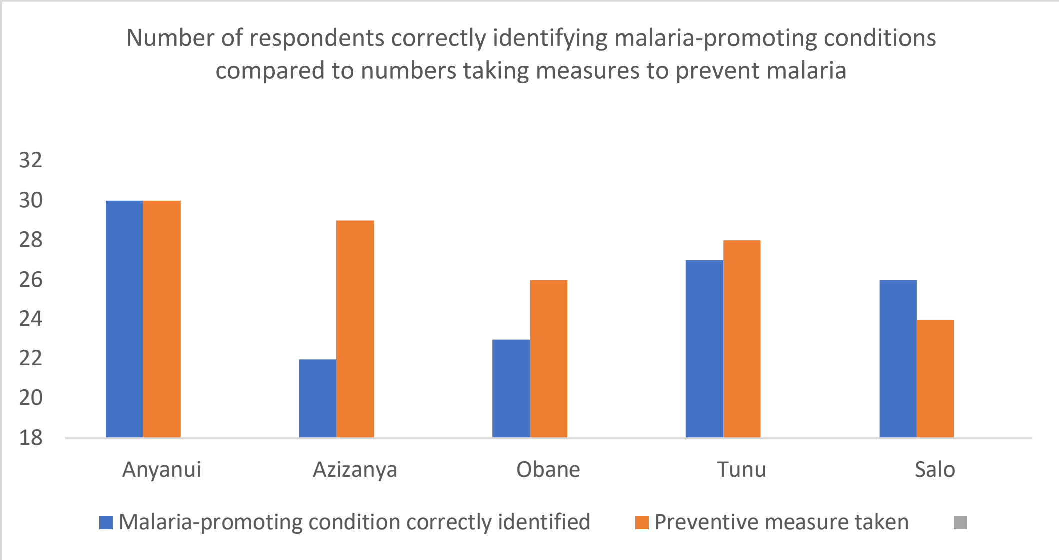

Figure 37: Number of respondents correctly identifying malaria-promoting conditions compared to those taking measures to prevent malaria infection on a community basis.

Although not all respondents in the degraded mangrove community (Azizanya) were able to correctly associate malaria with the appropriate causal conditions, nearly all of them attested to taking at least one valid preventive measure against infection. This might be attributable to the extensive sensitization programmes undertaken to promote use of ITNs, even in communities where levels of formal education may not be sufficient for residents to fully understand how malaria is transmitted. This situation was interestingly slightly different from the non-mangrove community of Salo, where despite 26 out of 30 participants correctly identifying causal conditions, only 24 of them were taking measures to prevent the disease (see Figure 37). Common reasons in the responses about why preventive measures may not be taken are the insufficiency of nets for all members of the household, or discomfort associated with sleeping in nets. Unfortunately, given the cost involved with some of the protective measures, not all residents of such communities deem alternative means of malaria prevention worth spending scarce resources on. This finding suggests that most people take measures against malaria provided they are provided for free as a government intervention, or unless they are affordable and readily available.

The general trend in malaria incidence from respondents' perspectives points to a reduction in incidence over time in all communities except Azizanya, where the highest number of responses indicating an increase in incidence (14) was recorded (Figure 38 and Figure 39). The healthy mangrove community of Tunu had 27 out of 30 respondents reporting a decrease in incidence, signifying the greatest proportion on a community-by-community basis. For people reporting 'no perceivable change' in incidence (25 in total), the majority were found in the non-mangrove community of Salo. Similar numbers were however reported in the degraded mangrove village of Azizanya (6) and in the healthy mangrove community Anyanui (6). The degraded mangrove village of Azizanya was the only location with number of respondents reporting no change or increase in incidence together (20), exceeding those reporting a decrease incidence (10).

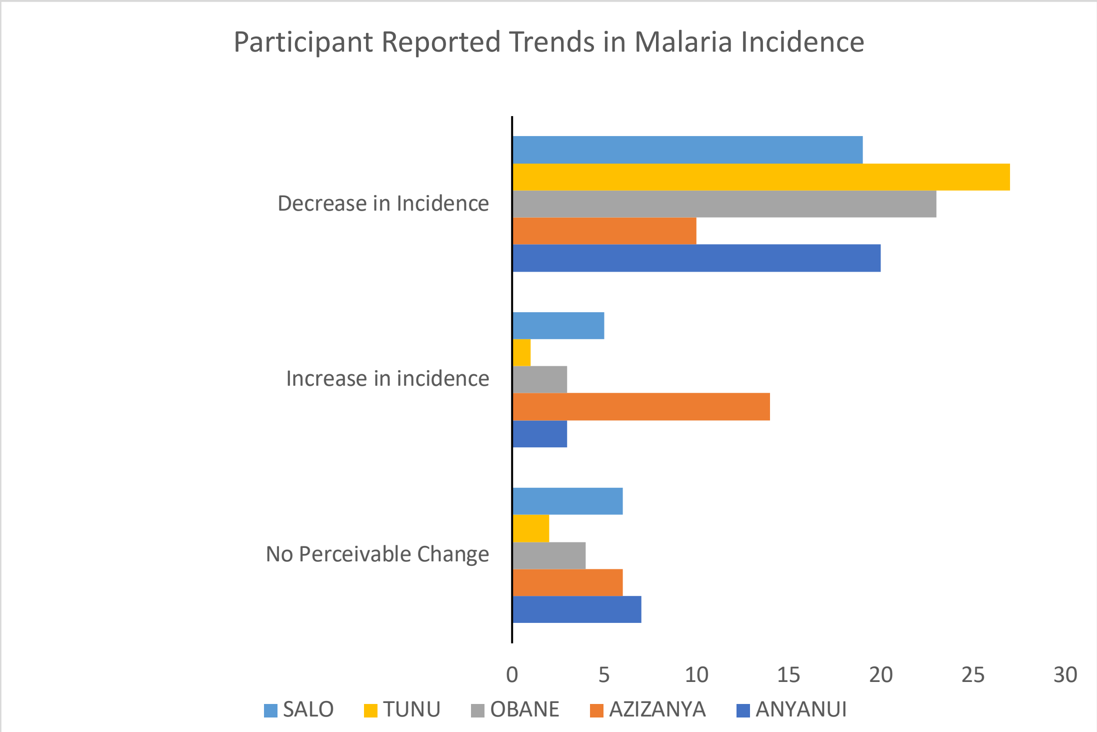

Figure 38: Numbers of participants reporting the three investigated trends in malaria incidence for each community over the recall period.

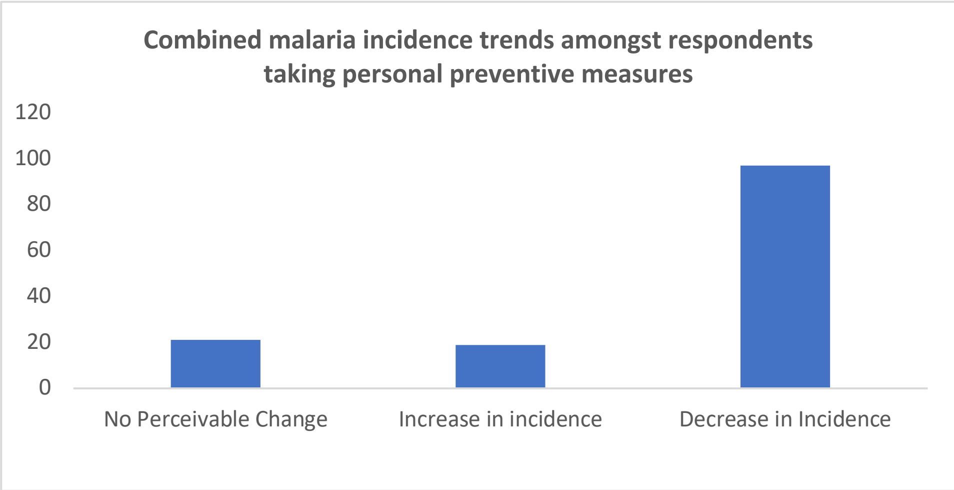

Figure 39: Numbers reporting the general incidence trends amongst respondents taking at least one personal preventive measure against mosquito bites over the recall period.

The use of ITNs, which are usually freely distributed to rural households, expectedly emerged as the key anti-malaria intervention that applies to all communities. For the few outlying participants who allude to taking no interventive measure against mosquito bites, there is usually a corresponding admission to either no change or an increase in malaria incidence. Within this group, communities with the highest numbers of participants reporting no reduction in malaria incidence are Salo, a non-mangrove community (5 participants); and Obane, a restored mangrove village (4 participants, Figure 40). For most respondents who report taking at least one preventive measure against mosquito bites, there is usually a corresponding admission of a reduction in malaria incidence (Figure 41).

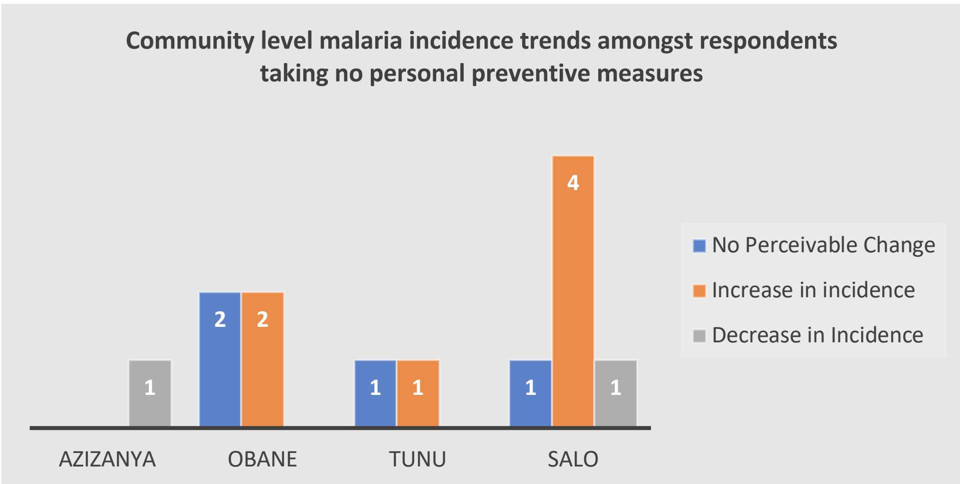

Figure 40: Numbers reporting the general malaria incidence trends amongst respondents taking no personal preventive measures. Anyanui is not represented because all residents report as least one preventive measure taken

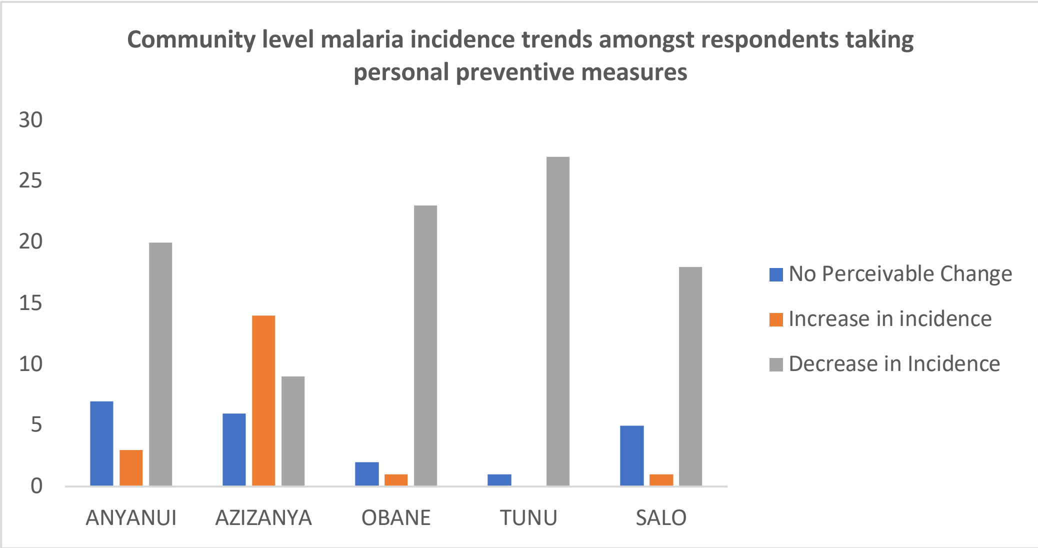

Figure 41: Community-level malaria incidence trends amongst respondents following implementation of at least one personal preventive measure against mosquito bites over the past decade.

5.3.3 Developments in Confirmed Hospital Cases

The trends reported in participant responses match with information supplied by the hospitals, for which the trendline indicates a gradual decline in incidence from 2012, when data collection began, until present (Figure 42). Figures decreased from a reported 975 malaria cases in the Ada east district in 2012, to 514 in 2019. In the Keta district (now split into Anloga and Keta), cases have seen a similar decrease from 1211 in 2012 to 615 in 2019. These figures represent 47.3% and 49.2% decrease in incidence for the Ada East and Keta districts, respectively. With respect to confirmed cases being offered a first anti-malarial treatment, a similar decline is observed. Numbers dropped in Keta district by 94.1% from a 2012 figure of 1460 to 86 in 2019, while Ada East saw an 81.2% reduction from 514 to 97 within the same period (Figure 43). All the afore mentioned figures are reported per 100,000 patients attended to institutionally (i.e., at the district hospitals).

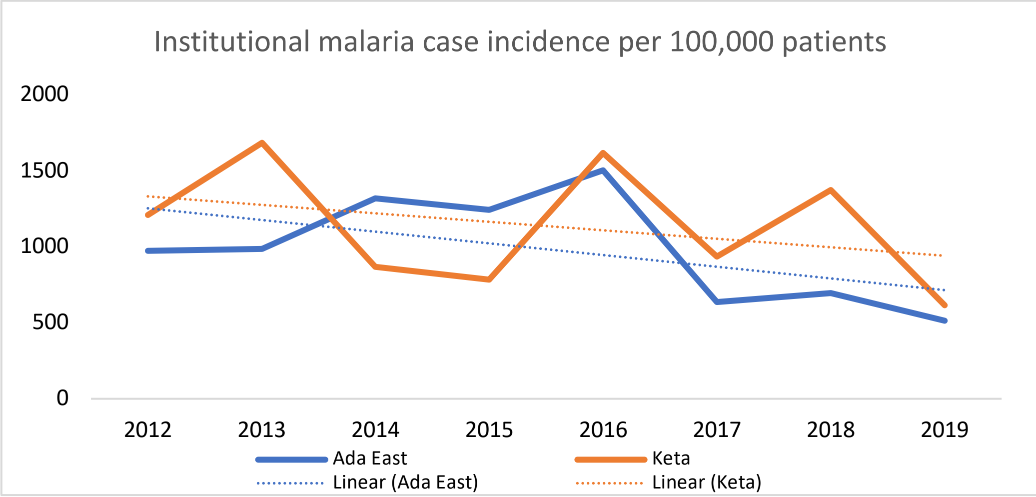

Figure 42: Institutional malaria case incidence trends per 100,000 hospital patients for both case study districts

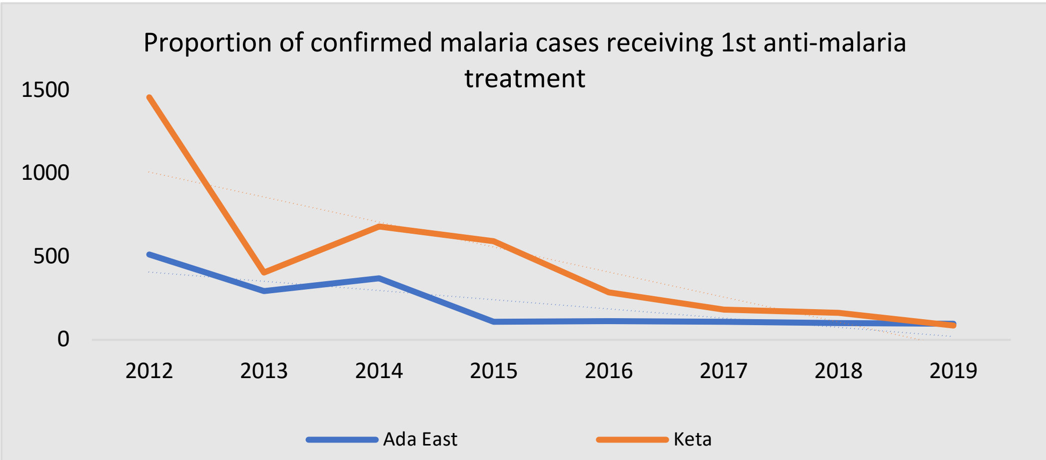

Figure 43: Changing numbers of hospital-confirmed malaria cases receiving 1st anti-malaria treatment over time.

5.3.4 QCA RESULTS

5.3.4.1 Truth Table Analysis

The completed fsQCA truth table for this study, which captures characteristics of the individual participants as 'cases' of the research, is presented in Table 16. For this truth table a total of 25 or 32 configurations, along with fifteen logical remainders emerged. This means that out of the 32 possible causal configurations, only 17 were displayed by the cases contained in the data. Configurations which were not observed in any cases (remainders) were omitted from the presented truth table, as they were inconsequential to the interpretation of eventual solution terms. The different rows represent the possible configurations of the causal conditions, and the outcomes observed along with those configurations.

Text Box 1: Recap of QCA process

1. Determine from the transcribed questionnaire data for the four mangrove communities (Anyanui, Azizanya, Obane, and Tunu) if subjects report a reduction or increase in malaria incidence over time (typically over the last decade).
2. Produce a data matrix which cross-tabulates the 5 investigated conditions in table 1 against the observed outcome
3. In the data matrix, dichotomise the membership scores as present (1) or absent (0) for the causal conditions and in relation to the outcome for each case
4. In respect of case-by-case set membership for the outcome set, allocate scores based on the framework in figure 34 and input into the data matrix
5. Enter the completed data matrix into the fsQCA software, designating the outcome and condition sets appropriately
6. Generate 'truth table' with causal configurations and consistency scores
7. Undertake the Boolean minimisation process on truth table using the fsQCA software to arrive at the full range of solutions (simple, intermediate, and parsimonious)
8. Conduct sensitivity test using different measures of fit and interpret intermediate solution(s) using case information and theoretical framework.

Rihoux and Ragin (2008) recommend that analysis of necessary conditions be conducted for fuzzy sets ahead of the truth table analysis, especially for studies where a hypothetical prediction of necessary conditions has been made. In such instances, the conditions identified after the initial necessity analysis can then be omitted for the truth table, which essentially is an analysis of sufficiency. No hypothesis regarding necessary conditions has been put forward in the present study, and as such all the 5 selected conditions were included in the initial truth table analysis.

Rows 1 to 7 of the truth table (Table 16), which have 'raw consistencies' of greater than the adopted threshold of 0.8, signify the configurations that most consistently give rise to an observation of the outcome 'reduction in malaria incidence over time' (RMI). Rows 8 to 17 on the other hand show the configurations that are negative for the outcome, so that whenever those configurations were observed in the data, the outcome was absent. Row 11 shows the configuration exhibited by the highest number of case (27), but these cases did not exhibit the outcome, whereas configurations in rows 6 and 7, although positive for the outcome, were exhibited by just one case each.

Table 16: Solution 1 QCA Truth Table indicating possible condition configurations and the resultant outcomes for a case frequency cut-off of 1 and a consistency cut-off of 0.8.

Row No.	RAT	IWQ	MLC	BCA	MPM	number	RMI (Outcome)	raw consistency
1.	0	0	1	0	1	2	1	1
2.	1	1	1	0	1	14	1	0.957143
3.	1	1	0	1	1	6	1	0.933333
4.	1	1	1	1	1	17	1	0.905882
5.	0	1	0	1	1	6	1	0.8
6.	0	0	1	0	0	1	1	0.8
7.	0	1	1	1	1	1	1	0.8
8.	0	1	1	0	1	19	0	0.736842
9.	0	1	0	0	0	3	0	0.666667
10.	1	1	0	0	1	9	0	0.644444
11.	0	1	0	0	1	27	0	0.444444
12.	0	1	1	0	0	2	0	0.2
13.	1	1	0	1	0	1	0	0.2
14.	0	0	0	0	1	6	0	0.166667
15.	1	1	1	0	0	2	0	0.1
16.	1	1	1	1	0	2	0	0.1
17.	1	1	0	0	0	2	0	0

A cursory look at the contracted truth table (cases not displaying the outcome omitted) suggests that no condition is necessary in this study (Table 17). This is because the results show that for every condition, at least one configurational row that is positive for the outcome exists where that condition is absent. Nonetheless, it is possible for a combination of conditions to be necessary for the outcome. Thus, as presented in Table 20 later, an analysis of necessary conditions was performed prior to generating a second truth table, with IWQ (Improved water quality) and MPM (Malaria preventive measures) exhibiting the highest consistencies for the outcome. This result was inputted into an alternative truth table analysis discussed later ((Table 21), where these two uncovered 'necessary conditions' are omitted.

Table 17: Contracted truth table for conditional configurations with a membership score of more than 0.5 in the outcome set. Absent conditions within configurations are shaded blue.

RAT	IWQ	MLC	BCA	MPM	number	RMI Outcome	raw consistency
0	0	1	0	1	2	1	1
1	1	1	0	1	14	1	0.957143
1	1	0	1	1	6	1	0.933333
1	1	1	1	1	17	1	0.905882
0	1	0	1	1	6	1	0.8
0	0	1	0	0	1	1	0.8
0	1	1	1	1	1	1	0.8

5.3.4.2 Analysis of Sufficiency for the Outcome 'reduction in malaria incidence'

5.3.4.2.1 Analytic Framework

Miller (2018) argues that intimate case knowledge might be better applied in interpretations of causal patterns in small-N QCA than in larger-N studies. However, it is the contention in this instance that the fraction of cases exhibiting the solution configurations, ('coverage' in QCA terms) is wide enough to facilitate a meaningful iteration between the solution terms, empirical case information and the aggregated findings on a community-by-community basis. The interpretations of solution terms in this study are grounded on the causal relationships outlined in the conceptual framework previously described in Figure 25.

In social science enquiry, the frequent problem of 'limited diversity of reality' means that some of the possible configurations that could lead to the observation of the outcome may not be exhibited by any of the cases. This phenomenon is what accounts for the substantial number of logical remainders in QCA for larger-N datasets, which were fifteen in the present study. Logical remainders are excluded in some of the concluding logical minimisation pathways of the truth table and included in others. The problem of limited diversity is overcome by using 'simplifying assumptions' or 'counterfactuals' to account for whether a logical remainder would have led to observation of the outcome or not. Counterfactuals have been relied on in this way in causal inference methodologies (Brady, 2008; George and Bennett, 2005; King et al., 1994; Morgan and Winship, 2015). As pointed out by Legewie (2013), this practice is useful because presence and absence of a given factor cannot be concurrently observed in one case. In the present study, simplifying assumptions are supported by the condition justifications given in Table 14. In the fsQCA software, the logical minimisation algorithm (Quine-McCluskey) was directed to assume for the first solution approach, that the outcome is likely to occur when all the five conditions are present. Three distinct types of solutions are obtainable, depending on the nature of configurations considered.

Firstly, a 'complex solution' is generated by the software, which makes use of no logical remainder configurations in analysing the conditions sufficient for the outcome, sticking strictly instead to the facts observed in the data. A complex solution is however difficult to interpret since no theory-based simplifying assumptions can be made in its generation. A second 'parsimonious solution', on the other hand, although the shortest and thus easiest to interpret, makes use of all the logical remainders, under the bold assumption that if remainder configurations had occurred, they would have been sufficient for the outcome. It therefore analyses all possible configurations, including those involving improbable assumptions and thus implausible theoretical explanations. It might therefore not be possible to interpret the resultant solutions terms of a parsimonious solution entirely and satisfactorily in the last step, as decisions on remainders are made automatically regardless of whether they theoretically make sense. The 'intermediate solution' is the third type of solution, which is derived as a subset(s) of the complex solution terms that form the parsimonious solution. It omits the complex solution terms which are absent in the parsimonious solution, and other redundant terms, provided they are theoretically not expected to lead to the outcome (Schneider and Wagemann, 2012). The intermediate solution uses only so called 'easy counterfactuals' (Ragin and Sonnet, 2004), which are the logical remainders with configurations which although not observed in the data, can be explained by more probable assumptions. In other words, these easier 'counterfactuals' are assumptions about remainders composed of conditions or combinations of conditions that theoretically would most realistically have led to lead to the outcome, if they had occurred in the data. Solution terms are all sufficient for the outcome, and in this study only the causal recipes of the intermediate solutions only are considered for interpretation for the reasons outlined.

Using the calibration framework defined in the methods section and applying frequency and consistency cut-offs of 1 and 0.8 respectively, the sufficient solution terms in Table 18 were derived for the outcome 'Reduction in Malaria Incidence over time". This is labelled 'Solution Approach I.' After an analysis of necessity, necessary conditions were omitted for a second solution approach, designated as 'Solution Approach II.'

5.3.4.2.2 Solution Approach I (substantive calibration, all conditions analysed)

According to the perspectives sampled from the four mangrove communities studied, the three causal recipes captured in Table 18 are sufficient to elicit a reduction in malaria incidence. This reveals out how more than one condition is of causal value in the observed malaria trends, and that more than one conjunctural combination of causal conditions exists for the outcome. The solution terms in Table 18 constitute the intermediate QCA solution obtained and are the causal recipes that describes how mangrove related conditions work, in conjunction with personal protective measures, to elicit the outcome. Together, they contribute to a minimal formula given as follows:

$$\sim IWQ * MLC + RAT * MLC * MPM + IWQ * BCA * MPM \rightarrow RMI$$

This minimal formula implies that a reduction in malaria incidence (RMI) as an outcome in the mangrove communities along the Volta Estuary, is most likely to be brought about by the following combinations of conditions:

1. The absence of 'improved water quality' (~IWQ) but the presence of arrested 'mangrove land conversion' (MLC) together, OR
2. The presence of 'reduced ambient temperature' (RAT), arrested 'mangrove land conversion' (MLC) and 'malaria preventive measures' (MPM) together, OR

3. The presence of ‘improved water quality’ (IWQ), ‘biological control agents’ (BCA) and ‘malaria preventive measures’ together.

These 3 causal recipes can logically be said to be sufficient for explaining at least half of the observed reduction incidences of malaria incidence (solution coverage 0.54) and are highly consistent in eliciting the outcome (consistency 0.91).

Table 18: Solution Approach I Truth Table analysis: Intermediate solution for outcome frequency and consistency cut-off of 1 and 0.8, respectively. Note: ~ means absence of a condition

Solution Term	*Raw Coverage*	*Unique Coverage*	*Consistency*
*~IWQ*MLC*	0.0356234	0.0356234	0.933333
*RAT*MLC*MPM*	0.366412	0.170483	0.929032
*IWQ*BCA*MPM*	0.338422	0.142494	0.886667
Solution Coverage	0.544529		
Solution Consistency	0.910638		

The first causal recipe by interpretation suggests that for the communities where water quality improvements have not been observed or acknowledged as being due to mangrove presence, there is still an opportunity for mangroves to contribute to a reduction in malaria incidence. This opportunity lies in the curtailment of mangrove land conversion, which is a known pathway for making more *Anopheles* mosquito-friendly habitats available (Walsh et al., 1993). Provided mangrove land is not converted for other purposes such as agriculture or salt winning, there is a potential benefit to be derived by way of malaria vector control, irrespective of whether personal protective measures are taken to prevent mosquito bites or not. By arresting mangrove land conversion, the risk of creating more enabling habitats for mosquito breeding can be significantly reduced. Controlling the emergence of favourable vector mosquito breeding conditions is an established pathway to malaria control (Watson, 1921; Utzinger et al., 2001; Vanek et al., 2006; Killeen et al., 2004). This is the only solution term which involves only mangrove related conditions exerting an influence on malaria outcomes, without the need for personal preventive measures to be taken. This combination of conditions however, judging from the low raw and unique coverage of

0.04, only accounts for a minute proportion of the cases for which a reduction of malaria incidence is observed.

An impact of water quality decline on malaria vector behaviour is usually to exacerbate proliferation and biting activity, potentially leading to an increase rather than a reduction in malaria incidence. In the degraded mangrove village of Azizanya, responses denote the only instances where water quality decline were explicitly mentioned in relation to consequences of mangrove land conversion. This is consistent with the findings of Berg et al., (2010), who highlight how water quality suffers due to losses in wetland vegetation cover. Theoretically speaking therefore, cases in Azizanya were not expected to fall within this solution configuration where, absence of water quality improvement needs to occur alongside arrested mangrove loss to generate a 'reduction in malaria incidence' outcome, and they fittingly did not. Obane is another community where water quality mentions were absent (inland mangroves only), but arrested mangrove land conversion was palpably present, given mangrove use restrictions that were in place. It was therefore expected that cases in Obane would display the causal configurations in the first solution term in this approach. This was however not the case. A closer look at the cases where positive outcomes were not observed in Obane revealed that those cases could not correctly identify either malaria symptoms or causes, which resulted in appropriate personal protective measures not being taken in contrast with the rest of the population. Such people not taking precautions that were otherwise common within the wider population can thus be assumed to have been at a higher risk of contracting malaria than the general population. Their malaria experiences were consequently less favourable and thus at variance with the expected effects of the first causal recipe in this solution approach. The cases for which this first solution term applies are only found in Tunu in reality (case code TN), a community with healthier-looking mangroves (Table 19). In Tunu, while cases do not necessarily mention water quality improvement indicators, there is a clear aversion towards mangrove land conversion, which is evidenced by the fact that mangrove replacement and farming is an active way of life. Whereas the combination of conditions contained in the first solution term almost certainly results in the outcome (0.93 consistency), it cannot be overly generalised as a causal recipe for the wider population as confidently as the other combinations, given its low raw coverage of 0.04.

The second solution term for this first approach shows a reduction in ambient temperature, resulting from a more extensive mangrove vegetation cover, working in conjunction with arrested 'mangrove land conversion' to reduce malaria incidence if 'malaria protective measures' against mosquito bites are also taken. Compared to the first solution term, this second combination of conditions accounts for a greater number of the cases where a reduction in malaria is acknowledged (coverage 0.37) but is equally consistent in eliciting the outcome (0.93 consistency each). The cases for which this second combination applies are found in Anyanui and Tunu (cases with code 'AN', 'TN', Table 19, row 2), two communities with comparatively healthier mangroves, and where mangrove revegetation is an integral part of local culture.

Table 19: Cases belonging to the respective Solution Approach 1 terms.

Cases with greater than 0.5 membership in solution term MLC*~IWQ	TN2, TN24 and TN 27
Cases with greater than 0.5 membership in solution term RAT*MLC*MPM	AN1, AN10, AN11, AN12, AN13, AN14, AN29 TN1, TN4, TN5, TN6, TN7, TN8, TN9 TN10, TN11, TN13, TN15, TN16, TN17
Cases with greater than 0.5 membership in solution term MPM*BCA*IWQ	OB2, OB4, OB7, OB11, OB15, OB16, OB17, OB20, OB25, OB27, OB28, OB29, AN1, AN12, AN13, AN14, AN29, TN1, TN9

A more extensive mangrove vegetation cover in these communities means that temperatures are more likely to be cooler, and mangrove land prospectively remains intact rather than converted for other purposes. Expectedly, cases displaying the conditions in this second causal recipe along with the RMI outcome are found in these two communities, where cases attested to cooler temperatures resulting from a more extensive mangrove cover. As ambient temperatures decrease, *Plasmodium spp.* maturation time in the mosquito also increases, rising from 12 to 30 days for a temperature reduction from 25°C to 20°C, thus minimising transmission risk (Stresman, 2010). Cooler temperatures are also typically inhibitory to larval hatching, which has been observed to occur faster under elevated ambient temperatures of between 25°C - 30°C (Reiter, 2008). On the contrary, temperature increase up to 34°C hastens the processes leading up to pupation in juvenile mosquitos (Barreaux et al., 2018), ensuring that more adults emerge sooner to pose malaria risk. Biting rates are also amplified with rising temperatures, due to faster blood meal digestion rates (Afrane et al., 2012).

The third QCA solution term for this first approach indicates that for people taking 'malaria preventive measures' against mosquito bites, the presence of 'biological control agents' and 'improved water quality' will almost certainly lead to a reduction in malaria incidence (consistency 0.89). Again, this third solution term explains observation of the outcome to a greater degree than the first solution term (coverage 0.34) and additionally applies to a more diverse collection of cases. Cases within the sampled population exhibiting this third combination of conditions can be found in three different communities – Obane, Anyanui and Tunu, all of which have thriving mangrove ecosystems (Table 19, Row 3). Obane (case code 'OB') is the location of a reforested mangrove project which has usage restrictions in place to halt land conversion, whereas Anyanui and Tunu harbour mangroves which are in relatively sustainable cut-replant cycles of use. In Anyanui and Tunu, probing case characteristics revealed that biological control agents abound in the form of plentiful fisheries which respondents readily associated with mangrove presence. In Obane a diverse non-fisheries wildlife and abundant competing insect species observed by residents are more likely to be involved in any biological control exerted on the various stages of the malaria vector life cycle. A diverse array of wetland biological control agents such as algae, bacteria, nematodes, copepods, and predatory insects are known to be lethal to mosquitoes (Rey et al., 2012). Taken together, these characteristics suggest that replanting mangroves, an action linked to improved water quality and the abundance of biological control agents of the malaria vector, can work in complementarity with personal preventive measures to effectively curb malaria risk.

5.3.4.3 Analysis of Necessity (and Solution Approach II)

As previously stated, a cursory perusal of the substantive truth table does not immediately suggest the existence of necessary conditions for the outcome. This is because for every condition analysed, there is at least one configuration where the outcome is observed in the absence of that condition. Moreover, the theoretical background to this study was not conceptualised as involving any 'necessary conditions', as the data did not point to any instance where any of the conditions selected for analysis was constantly identified. Against this background therefore, for the first QCA approach (dubbed Solution Approach I), no conditions were excluded from the logical minimisation process on account of being an explicitly necessary condition. Nonetheless, a necessity analysis was conducted (Table 20), to account for a situation where necessary conditions could be obscured in the final solution. The results paved way for a second QCA approach where necessary conditions were omitted from the truth table analysis (Solution Approach II).

Table 20: Analysis of Necessary Conditions for the outcome variable 'Reduced Malaria Incidence'

Conditions Tested	*Consistency*	*Coverage*
RAT	0.519084	0.769811
IWQ	0.951654	0.673874
MLC	0.600509	0.786667
BCA	0.343511	0.818182
MPM	0.951654	0.699065
*IWQ*MPM*	0.989822	0.653782

For this analysis, conditions were tested individually in the fsQCA software to determine how consistently they are observed along with the RMI outcome, and to reveal what proportion of the cases these occurrences can be found in. In other words, the goal was to find out how many of the cases were positive for each condition and the RMI outcome together. From the results, improved water quality and malaria preventive measures have remarkably high consistencies (0.95 each), implying that for the cases where they are present, the RMI outcome is almost always observed. Because the outcome set is supposed to be a subset of the set of necessary conditions, such conditions need to be essentially present at every occurrence of the RMI outcome, suggesting a required consistency of 1. However, in fuzzy set QCA the recommended threshold for necessity analysis is 0.9 (Dul, 2016). On that basis, although no necessary conditions are present in absolute terms in this study, necessity analysis according to accepted fsQCA standards revealed two necessary conditions for the RMI outcome for a consistency threshold of 0.9. An analysis of the two relevant conditions together (IWQ*MPM) revealed an even higher consistency (0.99) with the observed outcome (Table 20). This leads to the conclusion that IWQ and MPM are necessary for a reduction in malaria incidence to be observed. Based on this conclusion, and in accordance with the previously stated recommendations of Rihoux and Ragin (2008), a second approach of QCA truth table analysis was conducted excluding the necessary conditions IWQ and MPM. The resultant truth table and solution terms are presented in (Table 21 and Table 22, respectively.

(Table 21: Solution Approach II truth table analysis of configurations of conditions RAT, MLC, and BCA along with the associated outcomes and consistency values. Note: necessary conditions MPM and IWQ are omitted

Row No.	RAT	MLC	BCA	Number of cases	RMI Outcome	raw consistency
1	**1**	1	0	16	1	0.85
2	**1**	0	1	7	1	0.828571
3	**1**	1	1	19	1	0.821053
4	**0**	0	1	6	1	0.8
5	**0**	1	1	1	1	0.8
6	**0**	1	0	24	0	0.716667
7	**1**	0	0	11	0	0.527273
8	**0**	0	0	36	0	0.416667

Table 22: Solution II Intermediate solution without necessary conditions for RMI outcome, with frequency and consistency cut-off of 1 and 0.8 respectively

Solution Term	*Raw Coverage*	*Unique Coverage*	*Consistency*
BCA	0.343511	0.145038	0.818182
*RAT*MLC*	0.371501	0.173028	0.834286
Solution Coverage	0.516539		
Solution Consistency	0.828571		

Without the necessary conditions, five out of the possible 2^3 (8) configurations are shown to be positive for the outcome variable RMI (Rows 1-5, (Table 21), with a case frequency cut-off of 1 and consistency cut-off of 0.8. The last three rows show configurations for which the outcome was not observed, and these configurations account for a total of 71 out of the 120 total number cases. The minimal formula obtained after logical minimisation without the 'necessary conditions' is as follows:

$$BCA + RAT * MLC \rightarrow RMI$$

This means that either the presence of 'biological control agents' as a condition on its own, or the presence of 'reduced ambient temperature' and arrested 'mangrove land conversion' together, are sufficient to produce the RMI outcome. Because 'improved water quality' and 'malaria preventive measure' together have been identified as necessary conditions prior, the two sufficient solution terms in the new minimal formula are automatically thought to be valid in conjunction with those two necessary conditions. The interpretation can thus be taken to be that provided water quality improvements are present, and malaria preventive measures are taken, a reduction in malaria incidence will be observed if either:

1. Biological control agents are present, OR
2. 'Reduced ambient temperature' and arrested 'mangrove land conversion' are present together.

Written as a new wholesome minimal formula, the solution interpretation can be composed as follows:

$$IWQ * MPM * BCA + IWQ * MPM * RAT * MLC \rightarrow RMI$$

This minimal formula has a solution consistency of 0.83, and a solution coverage of 0.52 (See Table 22). The two solution terms that make up this new formula are like solution terms 2 and 3 in the initial truth table analysis where improved water quality, biological control agents and mangrove land conversion equally are implicated in the causal recipes. Cases for which the solution terms of 'solution approach II' apply are given in Table 23.

Table 23: Cases belonging to the respective Solution Approach II terms.

Cases with greater than 0.5 membership in solution term BCA*(MPM*IWQ)	OB2, OB4, OB7, OB11, OB15, OB16, OB17, OB20, OB23, OB25, OB27, OB28, OB29, AN1, AN2, AN11, AN12, AN13, AN14, AN29
Cases with greater than 0.5 membership in term RAT*MLC*(MPM*IWQ)	AN1, AN2, AN10, AN11, AN12, AN13, AN14, AN15, AN29, TN1, TN3, TN4, TN5, TN6, TN7, TN8, TN9, TN10, TN11, TN13

5.3.4.4 Analysis of Sufficiency for the Non-Occurrence of the RMI Outcome

Since QCA is based on Boolean rather than Linear Algebra, the occurrence of an outcome is conceptualised as being influenced by phenomena that could be vastly different from that for the non-occurrence of that outcome. Qualitatively speaking, the explanation for the presence of an outcome cannot be assumed to be merely a negation of the explanation for the outcome's absence (Greckhamer et al., 2018). Schneider and Wagemann (2012) therefore, advise that the configurations for the presence and absence of an outcome be analysed separately, to account for the potentially dissimilar causal models involved. The truth table for the condition configurations related to the negated outcome set (~RMI) is represented in Table 24.

Table 24: Truth table analysis of configurations of conditions sufficient for non-occurrence of the RMI outcome, and associated consistency values for a case frequency cut-off of 1

Row No.	RAT	IWQ	MLC	BCA	MPM	number	~RMI Outcome	raw consistency
1	**1**	1	0	0	0	2	1	1
2	**1**	1	1	0	0	2	1	0.9
3	**1**	1	1	1	0	2	1	0.9
4	**0**	0	0	0	1	6	1	0.833333
5	**0**	1	1	0	0	2	1	0.8
6	**1**	1	0	1	0	1	1	0.8
7	**0**	1	0	0	1	27	0	0.555556
8	**1**	1	0	0	1	9	0	0.355556
9	**0**	1	0	0	0	3	0	0.333333
10	**0**	1	1	0	1	19	0	0.263158

Row No.	RAT	IWQ	MLC	BCA	MPM	number	~RMI Outcome	raw consistency
11	**0**	1	0	1	1	6	0	0.2
12	**0**	0	1	0	0	1	0	0.2
13	**0**	1	1	1	1	1	0	0.2
14	**1**	1	1	1	1	17	0	0.0941177
15	**1**	1	0	1	1	6	0	0.0666667
16	**1**	1	1	0	1	14	0	0.0428571
17	**0**	0	1	0	1	2	0	0

Out of the 2^5 or 32 possible configurations, 17 were observed in the cases, with 6 configurations being positive for the outcome set 'absence of reduction in malaria incidence'. The intermediate solution terms that stipulate the causal recipes most consistently accounting for non-occurrence of the outcome 'RMI' are highlighted in Table 25, and are given by the following minimal formula:

$$\sim IWQ * \sim MLC * MPM + RAT * IWQ * \sim MPM + IWQ * MLC * \sim MPM \ \rightarrow \sim RMIb$$

The interpretation of the two solution terms indicates that for the absence of a reduction in malaria incidence to occur, the following combinations of conditions are most likely to be observed:

1. The absence of both 'improved water quality' and arrested 'mangrove land conversion' together with presence of 'malaria preventive measures', OR
2. The presence of both 'reduced ambient temperature' and 'improved water quality' together with absence of 'malaria preventive measures', OR
3. The presence of 'improved water quality' and arrested 'mangrove land conversion' together with absence of 'malaria preventive measures'.

The first solution suggests that even where people are taking preventive measures against mosquito bites, it is possible for an increase in malaria incidence to be observed. Such a situation arises when mangrove land conversion is rife, thus potentially disrupting ecosystem checks and balances and making more favourable habitats available for mosquito breeding. Water quality improvements must also be absent in such a scenario for no reduction in malaria incidence to manifest.

Table 25: Intermediate solution for non-occurrence of the outcome, with frequency and consistency cut-off of 1 and 0.8 respectively

Solution Term	Raw Coverage	Unique Coverage	Consistency
~IWQ*~MLC*MPM	0.120773	0.120773	0.833333
RAT*IWQ*~MPM	0.154589	0.0676328	0.914286
IWQ*MLC*~MPM	0.125604	0.0386474	0.866667
Solution Coverage	0.31401		
Solution Consistency	0.866667		

Cases for which the first solution term applies are found in Azizanya only, which is the community with degraded mangroves. Incidentally, that is the only community where people made comments about water pollution in relation to mangrove loss. Other communities reported more about state of fisheries, vegetation and wildlife when referring to consequences of mangrove loss and revegetation. Cases in Azizanya, which forms part of the Ada East District, also constituted the highest proportion of those reporting a relative increase in malaria incidence over time on community basis.

The second solution term gives an indication that even where temperatures have been kept cooler, and water quality improvements have been observed, these two mangrove-related conditions exert little curtailment effect on malaria unless personal preventive measures against mosquitoes are also taken. This second solution configuration applies to 7 cases spread across Obane, Anyanui and Tunu where the mangroves are faring well. Again, the third solution explaining non-occurrence of the RMI outcome points to a weak ability of mangrove conditions alone to curb malaria if personal protective measures against mosquitoes are omitted. Arresting mangrove land conversion and water quality improvements under healthy mangrove conditions, while expected to have desirable effect on malaria control, are implicated in non-occurrence of the desired RMI outcome. According to the analysis, such a situation is shown to consistently occur anytime personal protective measures against mosquito bites are not taken. The third solution term is exhibited by 6 cases in Anyanui and Tunu only, where mangroves are thriving.

5.3.4.5 Test For Sensitivity

The choices made in setting thresholds and allocating set membership scores for this study have been done based on conventions and best practice rather than according to rigid rules. Yardsticks for setting consistency and frequency cut-off for example depend on data characteristics such as sample size, number of observed case contradictions, calibration precision, and the strength of theoretical underpinnings found in nature. Schneider and Wagemann (2012) argue for consistency to be set high for small and medium N studies (usually 10-100 cases thereabout) and for studies where greater confidence can be found in literature about the conditions and calibration framework relied upon. They additionally advise for frequency cut-offs for sufficient configurations to be set at 1 for small to medium N studies, and alternatively at some percentage of total sample size when dealing with a larger number of cases. It follows that no universal values can be obtained from guidelines of this nature, and that case details dictate the eventual choices associated with these parameters of fit. The general preference however is that consistency thresholds chosen for sufficient conditions and configurations should be higher than 0.75 (Rihoux and Ragin, 2008).

In the current study, consistency and frequency cut-offs were set at 0.8 and 1 respectively, because only 120 cases were investigated. However, the theoretical scaffold for selecting causal conditions, and the assumptions made in predicting how those conditions potentially work to elicit the outcome, are based on literature that is still under development. In fact, this study was intended to illuminate and bridge a gap that was identified in the academic space regarding how mangroves influence malaria experiences. This means that not much precision nor confidence can be alluded to in terms of what is already known about the causal relationships. In that regard, some might consider a consistency threshold of 0.8 for sufficiency analysis as high for a sample size that is only 20% above the recommended margin. Emmenegger et al (2014) point out how varying the consistency threshold can provide an avenue to test the robustness of QCA results, especially where the solution coverage excludes a sizeable number of cases. To test the sensitivity of results in this study, the consistency threshold was reset at 0.7 instead of 0.8, to test how the solution terms are affected. The 0.7 selection was made because of the gap in consistency between configuration rows 8 and 9 in the solution approach I truth table (Table 16), which QCA experts like Schneider and Wagemann recommend as a pointer for setting an alternative consistency threshold. The resultant truth table and intermediate solution terms are provided in Table 26 and Table 27 respectively, with all the five conditions analysed. The minimal solution derived from this sensitivity test was as follows:

$$\sim IWQ * MLC * MPM + MLC * MPM + IWQ * BCA * MPM \rightarrow RMI$$

This solution translates into the following three causal pathways to the occurrence of the 'reduction in malaria incidence' (RMI) outcome:

1. Absence of 'improved water quality' and presence of arrested 'mangrove land conversion' together, OR
2. Presence of arrested 'mangrove land conversion' and 'malaria preventive measures' together, OR
3. Presence of 'improved water quality', 'biological control agents' and 'malaria preventive measures' together

Table 26: Alternative truth table (sensitivity test) of sufficient configurations for the outcome 'RMI' with frequency and consistency cut-offs of 1 and 0.7 respectively

Row No.	RAT	IWQ	MLC	BCA	MPM	number	RMI Outcome	raw consistency
1	**0**	0	1	0	1	2	1	1
2	**1**	1	1	0	1	14	1	0.957143
3	**1**	1	0	1	1	6	1	0.933333
4	**1**	1	1	1	1	17	1	0.905882
5	**0**	1	0	1	1	6	1	0.8
6	**0**	0	1	0	0	1	1	0.8

Row No.	RAT	IWQ	MLC	BCA	MPM	number	RMI Outcome	raw consistency
7	**0**	1	1	1	1	1	1	0.8
8	**0**	1	1	0	1	19	1	0.736842
9	**0**	1	0	0	0	3	0	0.666667
10	**1**	1	0	0	1	9	0	0.644444
11	**0**	1	0	0	1	27	0	0.444444
12	**0**	1	1	0	0	2	0	0.2
13	**1**	1	0	1	0	1	0	0.2
14	**0**	0	0	0	1	6	0	0.166667
15	**1**	1	1	0	0	2	0	0.1
16	**1**	1	1	1	0	2	0	0.1
17	**1**	1	0	0	0	2	0	0

Table 27: Alternative intermediate solution (Sensitivity test) for the 'RMI': outcome with frequency and consistency cut-offs of 1 and 0.7 respectively

SOLUTION TERM	*RAW COVERAGE*	*UNIQUE COVERAGE*	*CONSISTENCY*
*~IWQ*MLC*	0.0356234	0.0101781	0.933333
*MLC*MPM*	0.580153	0.3486	0.860377
*IWQ*BCA*MPM*	0.338422	0.132316	0.886667
solution coverage	0.722646		
solution consistency	0.860606		

When compared with the results of the previous truth table analyses (see Table 28), one solution term stands out as common in all three instances (term 3 in Table 27). In all approaches, 'improved water quality', 'biological control agents' and 'malaria preventive measures' are expected to elicit the outcome of reduced malaria incidence' when present together. The condition of 'reduced ambient temperature', which features in the second solution terms for the first two solution approaches, does not appear in the sensitivity test solution at all. This means that when a larger proportion of cases are considered, the RAT condition ceases to play a conjunctural role with other conditions sufficient for the outcome.

Table 28: Intermediate solutions from the two approaches compared with the alternative solution obtained from lowering consistency threshold from 0.8 to 0.7.

Solution Approach 1 (all conditions analysed) Solution coverage: 0.544529 Solution consistency: 0.910638	**Solution Approach II (necessary conditions IWQ and MPM omitted)** Solution coverage: 0.516539 Solution consistency 0.828571	**Solution Approach III (Test for sensitivity)** solution coverage: 0.722646 solution consistency: 0.860606
1. ~IWQ*MLC		1. ~IWQ*MLC
2. RAT*MLC*MPM	1. (IWQ*MPM) *RAT*MLC	2. MLC*MPM
3. IWQ*BCA*MPM	2. (IWQ*MPM) *BCA	3. IWQ*BCA*MPM

Lowering the consistency threshold in the sensitivity test raises solution coverage to 0.72, which is higher than the solution coverage obtained in the other two solutions, thus making it possible for a greater number of cases to be covered by the solution terms. It also marginally reduces the solution consistency from 0.91 to approximately 0.9. This means that while the adjusted solution would apply more accurately to a greater proportion of cases, the relevant cases would be almost equally consistent in displaying the outcome. When describing phenomena surrounding mangroves and reduced malaria incidence within the study region therefore, the links uncovered are slightly sensitive to thresholds set for some parameters of fit. They can also be generalised for the study population without significantly impacting the consistency with which they can be expected to lead to a reduction in malaria incidence.

5.3.5 Limitations of Study

It was expected that mangrove ecosystem monitoring data for the communities that lie within the purview of the Wildlife Department would be used in estimating ecosystem integrity improvements. This was particularly envisaged for the restored mangrove project established in Obane, to analyse trends of some ecological parameters of the mangrove environment that are theoretically expected to improve following revegetation. If this had been possible, the concept of ecosystem integrity improving with time following replanting could have been effectively verified in respect of the Volta Estuary. The quality of available data however proved to be problematic.

Reporting formats were inconsistent from site to site and did not account for unique mangrove characteristics beyond overall wetland assessment feedback contained in quarterly reports. In the absence of high-quality, targeted ecological monitoring data, the participant perspectives presented regarding ecosystem improvements remain unfortunately unverified.

The second limitation was in respect of available hospital data. The Ghana health service collates data on confirmed malaria cases at the district level, which was used to compare malaria incidence trends self-reported by participants in this study. Unfortunately, the aggregated data could not be broken down further to community levels, as information is collected at the lowest cross-community healthcare delivery tier rather than on a community basis. It was therefore impossible to deduce what proportion of the data utilised in presenting malaria infection trend is attributable to the sampled communities only. To minimise the effect of this shortfall, an additional non-mangrove community (Salo) was surveyed, which although excluded from the QCA analysis, offered an avenue to ascertain similarities in trend.

Owing to time and resource constraints, changes in vector behaviour were not directly measured in this study. Although theoretically deemed to be a potentially critical link between mangrove ecosystem integrity and malaria incidence, the effect that mangroves have on biting behaviour and parasite prevalence in the vector was not investigated. Such a venture would have involved spatio-temporal mosquito sampling, observation of biting behaviours and parasitic analysis of both saliva and blood meal contents, all of which were deemed to be beyond the scope of this study. Another layer of verification opportunity regarding disease transmission competence of mangrove mosquitoes, as compared to non-mangrove ones, was therefore lost.

5.4 SUMMARY, IMPLICATIONS AND CONCLUSIONS

This chapter has relied on theory-supported knowledge to assess the potential ways in which conditions elicited by mangrove ecosystem interventions work with health sector interventions to modulate physical health experiences. Specifically, the perspectives of people living close to mangroves exhibiting a variety of ecological and use characteristics, have been sampled in relation to malaria incidence experiences over time. Using QCA, the most outstanding combinations of intervention-related conditions working most consistently to reduce malaria incidence within the Volta estuary have been analysed. It has emerged that health sector interventions alone do not deliver the most desirable malaria outcomes. Instead, conditions occasioned by the ecological integrity improvements that accompany mangrove ecosystem interventions work in diverse ways to amplify the health benefits of public health interventions. This speaks to the value of cross-sector approaches towards realisation of more sustainable and effective health and well-being aspirations, where the most vulnerable ecosystems and populations are concerned. The findings and implications in respect of the guiding research questions that informed the specific research actions are recapped forthwith.

5.4.1 Mangrove Ecosystem Dynamics and Malaria-What We Know (RQviii)

Mangrove settlements along the Volta estuary have undergone a variety of changes with respect to the surrounding landscape, its ecology and the benefits derived therein. It appears that while mangroves are still an integral part of local culture among some communities, others have not been quite so fortunate. Ecosystem integrity losses have been progressive in some communities, embodied in this study by the state of the mangroves of the village of Azizanya, whereas others like Anyanui and Tunu have managed to maintain a sustainable revegetation culture. Proper mangrove management, including revegetation projects as observed in the village of Obane, has been largely effective in preserving some of the most vital ecosystem goods and services beneficial to humans. Given the circumstances, mangrove provisioning services in the form of wood products and support services for fisheries were the most acknowledged benefits, but more prominently in settlements with healthier mangroves. Access to these goods is restricted to mangrove landowners, who make them available for sale on the market, from where other community members can obtain them. In respect of anti-malaria therapy, medicinal supplies as a mangrove provisioning service were not identified in the sampled settlements, and most participants consider mangroves as promoters of malaria vector proliferation.

Association of mangroves with high mosquito abundance suggests a potential linear relationship between mosquito populations and a corresponding rise in malaria transmissions in nearby settlements. Literature suggests this may however not always be the case, with the possibility of different ecosystem processes working to elicit different vector population and behavioural dynamics under different ecological conditions. Mangrove deforestation is postulated to diminish detritus and nutrient richness in the ecosystem environment, which inhibits oviposition and the developmental processes that prop up adult populations and influence biting activity. This is part of a series of mechanisms proffered in explanation of the complex nature of mangrove-infectious disease relationships, which although beyond the scope of this study, pose outstanding questions for future research.

From a theoretical perspective, the impact of rising ambient temperature on mosquito populations, biting and malaria parasite transmission activity carried the most abundant evidence. Thinner tree canopies, arising from mangrove vegetation exploitation and dynamics of land use change, have been shown to give rise to more conducive mosquito habitats by promoting temperature-related consequences of greater sunlight penetration. However, both communities with diminished and intact mangrove tree canopies attested to pervasiveness of elevated mosquito populations in this study.

Moderate increase in ambient temperature not only decreases the time required for larval maturation to pupation and adulthood, but also increases hatching rates. This indicates an amplifying effect on adult mosquito population and thus parasite transmission probability. Additionally, marginally rising temperatures promote larva-sustaining provisioning microbial activity, thereby achieving higher larva-to-adult survival rates. Rising temperatures increase the rate of digestion of blood meals in mosquitoes, so that they are inclined to seek subsequent blood meals sooner. Because higher temperatures further reduce the parasite maturation time in the vector, increased biting activity significantly raises the chances of vector transmission of mature parasites to human hosts to cause malaria. Another uncovered consequence of deforestation-related temperature elevation is the fortifying effect on insecticide detoxification in mosquitoes, which threatens vector population control strategies.

Acknowledgment of temperature decline did not feature too dominantly in responses from the intact mangrove communities, mainly because two out of three of those communities have maintained an unchanging canopy cover. The one community with a revegetated mangrove forest produced the highest number of participant responses associating thicker mangrove tree canopies with temporal temperature decline. Finally, biodiversity losses arising from mangrove ecosystem degradation minimises opportunities for biological control of both juvenile and adult versions of the malaria vector. A similar effect prospectively arises under ecosystem disturbances that lead to water quality decline, where constraints are placed on competitive and biologically controlling species of juvenile and adult mosquitos. In such situations, the *Anopheles gambiae* complex of mosquitoes, which are specially adapted to thrive in polluted waters, retain the ability to proliferate and transmit anopheline disease.

5.4.2 Mangrove Ecosystem and Malaria Incidence Changes over Time (RQix)

A key part of this study was to investigate how revegetation of mangroves could potentially trigger ecosystem integrity improvements in a manner that reverses malaria-aggravating ecological changes. This objective was pursued by sampling perspectives of residents about the impacts of deforestation and revegetation on the supply of key self-identified provisioning mangrove ecosystem services. Respondents in mangrove communities readily recognized the most economically important benefits derived from mangroves. In most instances, this tends to be wood products for a variety of uses and a boost in fisheries, all of which are linked to human health and wellbeing. For these benefits, access is unhindered for mangrove landowners, but they are also available for sale to other groups of people. Residents of degraded and non-mangrove communities less-readily identified these benefits, having evolved their livelihoods and lifestyles to rely on scarce but often more costly alternatives. This group of people, although unable to determine how supply of these goods and services is affected by an improvement in the state of the ecosystem, largely agreed with the notion that said supply tends to be less favourable following ecosystem degradation.

Mangrove revegetation was deemed to be a worthwhile venture by residents who were confident in relating it to a matching improvement in the supply of provisioning and supporting mangrove ecosystem services. For the two intact mangrove communities, acknowledgment of the importance of vegetation in safeguarding supply of benefits is demonstrated in the religious replanting of harvested mangroves. In these two settlements, the community-established practice of active mangrove farming has led to a more sustained delivery of associated benefits. This situation contrasts with what pertains in the degraded mangrove community, where deforestation has led to loss of mangrove regeneration potential, with concomitant decline in supply of ecosystem services with time.

According to district level hospital data, the yearly aggregated number of confirmed cases of malaria in the Volta Estuary area has been on a steady decline over the past decade (2012-2022). Resident respondents in this study attest to this trend by reporting a corresponding decrease in household malaria incidence over the same period. Perspectives from communities with intact, healthy-looking mangroves, where replanting or restricted harvesting regimes are in place, constituted majority of decreased malaria incidence reports. The greatest proportion of households experiencing no perceivable change in incidence trends were those residing in degraded and non-mangrove communities. This was also true for households experiencing a rise in malaria incidence, even though most households surveyed were taking at least one preventive measure against mosquito bites. Households taking preventive measures report a decrease in malaria incidence, while those taking no measures exhibit either no perceivable change or an increase in incidence over the recall period.

5.4.3 Causal Relationships Between Mangrove Conditions and Malaria (RQx)

This study employs QCA methodology to uncover the links between theory-supported mangrove conditions and the malaria experiences of residents in the mangrove communities only (degraded, restored and 'healthy' mangroves). This QCA investigation was conducted considering a mitigation condition that is not related to mangroves, being the cross-cutting intervention of personal preventive measures against malaria (i.e., prevention of mosquito bites). The mangrove conditions investigated for their causal effect on malaria incidence were 'Reduced Ambient Temperature' (RAT), arrested 'Mangrove Land Conversion' (MLC), presence of 'Biological Control Agents' (BCA) and 'Improved Water Quality' (IWQ). These are conditions of well-functioning mangrove ecosystems for which theoretical evidence exists that have bearings on malaria vector and transmission dynamics. For these conditions, responses were categorised based on identification of proxy ecosystem observations predictive of their existence. For the investigated outcome of 'reduction in malaria incidence over time' (RMI), a Likert type scale was used to estimate the degree of agreement with the survey statement. After analysis with the fsQCA Software, three different solution approaches produced the causal recipes outlined in Table 28.

According to the QCA solution terms obtained, the absence of improved water quality works in conjunction with arrested mangrove land conversion to reduce malaria incidence. Secondly, provided malaria preventive measures are taken; either a reduction in ambient temperature and arrested mangrove land conversion on one hand, or improved water quality and presence of biological control agents on the other hand, will lead to a reduction in malaria incidence. This first solution approach is slightly sensitive to the threshold set for assessing how consistently the presence of a condition must lead to the outcome to be deemed causally significant. As this threshold is lowered from a raw consistency of 0.8 to 0.7, the role played by the condition of 'reduced ambient temperature' in the second causal recipe becomes redundant. An alternative analytical approach revealed that improved water quality and malaria preventive measures are conditions that must necessarily exist for a reduction in malaria incidence to be observed. Once these two necessary conditions are present, there are two possible causal pathways to the observation of a reduction in malaria incidence. The two pathways are either the presence of biological control agents; or, reduced ambient temperature and arrested mangrove land conversion occurring together.

5.4.4 Implications of Findings for Malaria Risk Management (RQxi)

The overarching finding of the study is that the theory-supported mangrove-related conditions selected for causality investigations, play a role in the causal recipes that most consistently lead to a reduction in malaria incidence in the Volta Estuary. Although these conditions do not all have to be present to elicit said outcome, they combine conjuncturally and asymmetrically to amplify the impacts of key public health intervention of personal preventive measures against mosquito bites.

5.4.4.1 The Ghana National Malaria Control Programme (NMCP)

Malaria is hyperendemic in Ghana, accounting for over 20% of hospital outpatient visits and admissions in 2017, and 9.7% of deaths for 2015 (Ghana Health Service, 2018). The devastating health and economic burden of the disease in the country led to a strategic control plan aimed at halving related morbidity and mortality rates by the year 2010 (Bawuah and Ampaw, 2021). This 2000-2010 plan sought to improve upon previous control measures by strengthening the existing therapeutic drug regimens via replacement with more effective Artemisinin based combinations. In the aftermath of the roll-out of the Millennium Development Goals and the 2006 Abuja declaration, a more ambitious plan was developed for the 2008-2015 period. This second plan had a 75% reduction target for lowering of malaria morbidity and mortality rates (Ghana, 2018). To overcome the challenges posed by regional and rural-urban differences in malaria burden, the National Malaria Control Program (NMCP) and its partners championed a more customised malaria control approach. This was aimed at tackling unique circumstances characterising malaria transmission, morbidity, and mortality patterns at the local level. A 2013 review of the national malaria strategy was thus conducted in collaboration with the 'Roll Back Malaria' partnership, culminating a new management plan (Figure 44). Under the current agenda of the resultant NMCP strategic plan, a 75% target was set for a reduction in malaria morbidity and Mortality compared to 2012 baseline figures (Country Coordinating Mechanism, 2018).

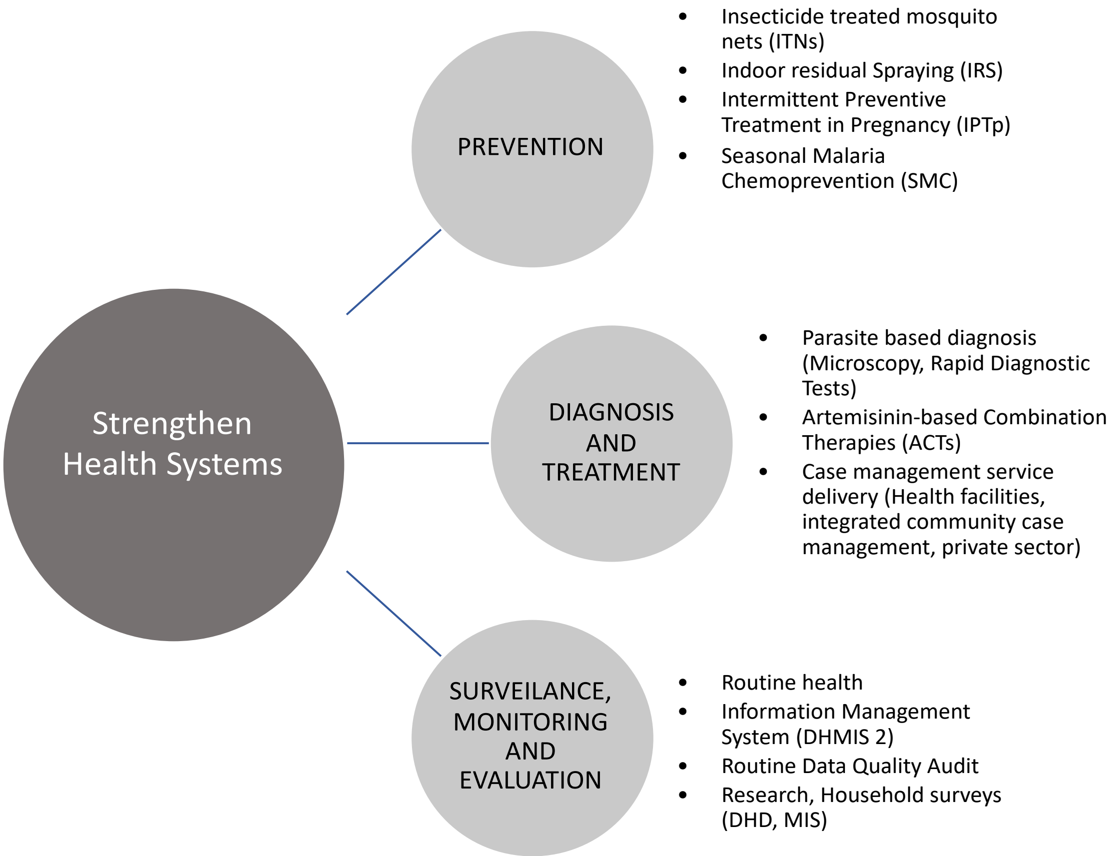

Figure 44: Priority programme areas of the Ghana National Malaria Control Program (NMCP) for strengthening health systems, represented by the radiating circles. The foundational goal is "to reduce the malaria morbidity and mortality burden by 75% (baseline 2012)

Four main aspects of the 2014-2020 NMCP strategic plan are related to the QCA-generated causal pathways to malaria incidence reduction (Figure 45). The proposed actions associated with these four aspects would augment attainment of programme objectives and boost overall malaria control. Contained in the diamond is a broad objective that is distinct from the QCA causal pathways.

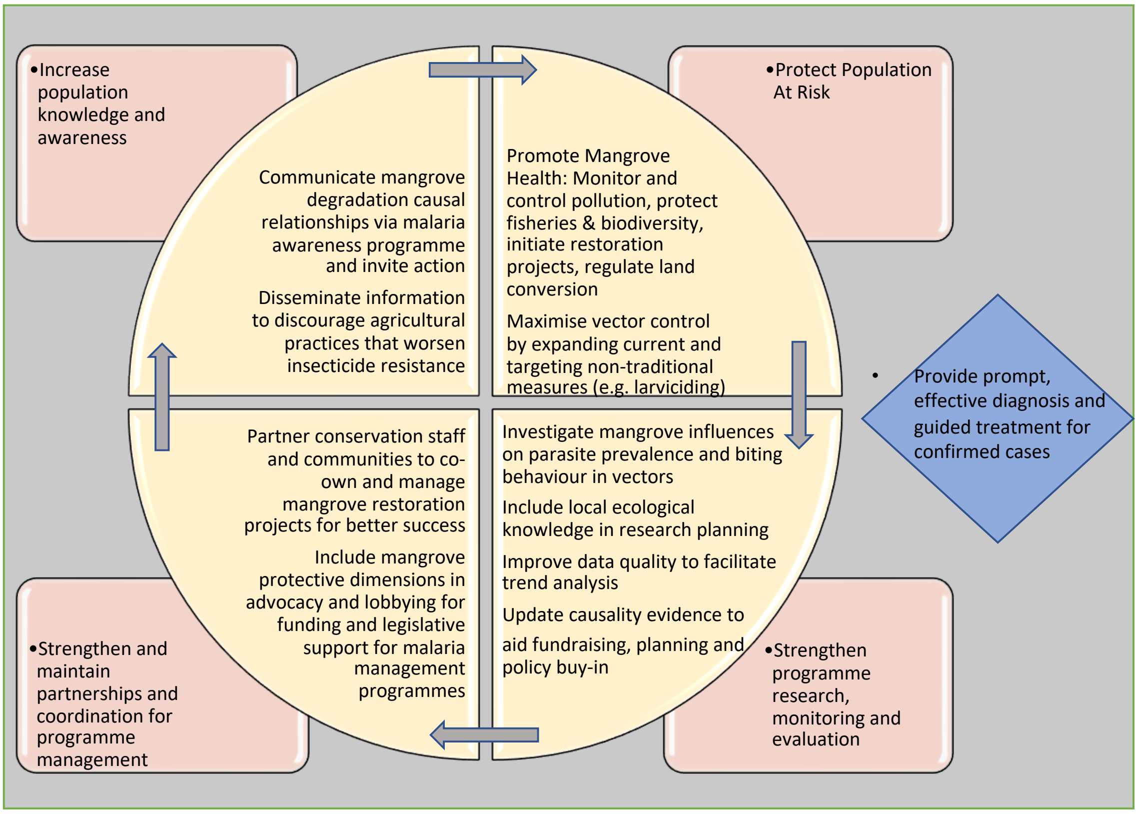

Figure 45: Strategic enhancement options for minimising malaria incidence in the Volta Estuary. Four rectangles represent main aspects of the NMCP where the actions in the text-filled quadrants can impact. The strategic policy aspect in the diamond is non-QCA related.

5.4.4.2 Protecting Population at Risk

One of the specific objectives of the latest NMCP (See Appendix N) was "to protect at least 80% of the population at risk with effective malaria prevention interventions by 2020" (Ghana Health Service, 2018) This has been pursued via a variety of integrated vector management initiatives, including distribution of free ITNs, IRS in areas with high parasite prevalence, seasonal malaria chemoprevention (SMP) and other environmental management strategies.

One of the necessary conditions identified in the causality analysis is IWQ, as associated with mangrove loss by respondents, albeit applicable to only a small fraction of cases. This was markedly true for few respondents in the degraded mangrove community, who outstandingly made this association, and who also reported the highest number of residents experiencing no reduction in malaria incidence. The link was further buttressed by the results of the analysis for non-occurrence of the RMI outcome (Table

25), which implicated absence of an improvement in water quality as a causal recipe component. In the NMCP strategy, there are initiatives that target control of both water-linked juvenile and adult vector forms. This implies that water quality improvement pathways involving mangroves, which eventually yield better mechanisms for biological control of mosquitos, could be useful considerations. Supporting natural fisheries, aquaculture and biodiversity would have equivalent results, while additionally expanding livelihood and nutrition options available to residents.

The results of this study also indicated that MPM, in the form of taking precautions against mosquito bites, is a necessary action for curbing malaria risk. This immediately highlights the major impact that the country's ITN deployment program has had on malaria prevention. This initiative, a key objective of the 2014 NMCP strategic plan, has been a tremendous success, as evidenced by the fact that only 13 out of the 120 participants in the study did not report ITN usage. The problem of skewed access to this preventive measure has, to an appreciable extent, been addressed by the free distribution programmes undertaken by the Ghana Health Service in hospitals and primary schools. ITN ownership and use increased from 30% in 2008 to 67% of the population in 2019, and from 21% in 2008 to 43% in 2019 respectively (Ghana Statistical Service, 2020). However, the NMCP is yet to achieve specific objectives of ensuring at least one ITN by every Ghanaian household and use of ITN by 80% of the population (Bawuah and Ampaw, 2021). Although present in most households, these nets must often be shared, as they hardly accommodate all household needs. Judging from participant comments, it does not appear that the '1 ITN per 2 persons' target of the NMCP has been met, so that inadequate ITNs per household leads to uncomfortable sleeping arrangements which could undermine patronage. Because of awareness creation initiatives that accompany ITN handout programs, participants were more aware today of the usefulness of these nets, and intimated that they would appreciate more nets. Ghana would thus benefit from expansion of ITN distribution rates, since these nets appear well patronised, and are having an outstanding impact on malaria incidence. While ITNs are not solely responsible for the current malaria experiences in any of the mangrove communities, their impact is amplified some of the most significant malaria-related ecological benefits of mangroves. Further, these ITNs must remain free for the poorest households, as affordability remains a major determinant of usage.

Rising levels of therapeutic drug and insecticide resistance and uncertainties shrouding vaccine roll-out suggest a need for re-evaluation of the current dominant vector control approaches. For countries in sub-Saharan Africa such as Ghana, an integrated strategy that always combines both ecological and transmission properties of the malaria vector is essential. Keiser et al. (2005) demonstrate the far-reaching effects of larval habitat control strategies, especially when deployed in conjunction with vector control measures like ITNs and IRS. Evidence of successful permanent and even temporary aquatic vector breeding site modification and management exists in literature (Killeen et al., 2004; Utzinger et al., 2001). Especially for the *A. gambiae* complex, which is prevalent in Ghana, an appreciable opportunity exists for modifications to both natural and man-made habitats found close to human homes and as preferred by the genus (Vanek et al., 2006). Such feats were successfully achieved before the DDT era (Konradsen et al., 2004), and are easily replicable. Interventions such as larviciding would control vector populations by eliminating juvenile forms in nearby aquatic ecologies in the study area, further strengthening effects of personal protective measures against mosquito bites.

5.4.4.3 Strengthening Partnerships, Co-ordination, and Awareness Creation

NMCP strategies have always involved collaboration between various stakeholders, including governmental, non-governmental, development funding and academic agencies etc. In advocating for greater private, public, and legislative sector backing for Ghana Health Service initiatives regarding wetland malaria management, it would be beneficial to explore mangrove protection dimensions. Such a move presents greater buy-in prospects form institutions seeking both health and environmental themes in their ‘corporate social responsibility’ and sustainability agenda, by offering comprehensive ‘one size fits’ all alternatives.

Because RAT was shown to work with arrested MLC in eliciting malaria reduction outcomes, health managers must partner wetland managers, such as the Wildlife

Division of the Forestry Commission of Ghana, to initiate and manage more mangrove restoration projects. Such initiatives would work to achieve the two-pronged target of promoting cooler temperatures and halting the mangrove ecosystem degradation that expands mosquito breeding habitats. These projects can then be planned in ways that sufficiently engender the mangrove ecological conditions that are most favourable for malaria control, without compromising other conservation and socio-economic targets.

Restoration projects could further be used as springboards for disseminating knowledge around links between mangrove degradation and malaria risk. The Ghana Health service holds a wealth of experience in this department, having successfully executed widespread malaria awareness creation programmes at community levels. Similarly, the Wildlife Division has engaged communities in wetland conservation issues in line with Ghana's Ramsar Convention obligations. By collaborating to replicate these awareness expansion initiatives, communities may be persuaded to adopt attitudes that minimise health risks of mangrove degradative activities. Both malaria reduction and 'wise wetland use' targets (Ramsar, 2014a) can then be achieved, while ensuring that residents continue to enjoy other economically beneficial ecosystem services. Further awareness on the role of pyrethroid-containing agricultural chemicals in insecticide resistance must also be targeted, while prioritising appreciation of and access to safer available alternatives.

5.4.4.4 Strengthening Research, Monitoring and Evaluation

To reinforce surveillance, monitoring, and evaluation of data, the NMCP must include local perspectives and trend analysis in designing and implementing research, to further explore the depth of mangrove influence on malaria outcomes. This could be as simple as including survey questions that sample household perspectives on changes in mangrove ecosystem conditions in Demographic Health Surveys (DHS) and using causal inference tools in analysis. To validate these perspectives, health agencies could indulge and sponsor better ecological data collection by environmental monitoring agencies active in the location, so that research on vector and parasite prevalence relative to the relevant mangrove ecosystem conditions can be facilitated.

Although the use of malaria preventive measures is a phenomenon that cuts across all communities, the degraded mangrove village where mangrove cover has declined reported less favourable malaria experiences. Participants here also reported abundance of mosquitoes; but their counterparts in healthy mangrove communities, in commenting about similar abundance, were quick to proffer a belief that mangrove mosquitoes do not spread malaria. For example, in response to researcher request for further relevant information, two different residents of the healthy mangrove community of Anyanui passed these comments:

“They tell us that mosquitoes give malaria, but I think that applies to mosquitoes in gutters and puddles around the houses, and not those within the mangroves”.

“There are a lot of mosquitoes in the mangroves, but they don't bite as aggressively as those in the village”.

These perspectives align with the theory-supported notions contained in the theoretical framework of the study, which point to a more complex interplay of habitat-vector dynamics beyond sheer abundance, leading to malaria risk aggravation. However, the causality analysis did not explore parasite prevalence dimensions nor mosquito biting trends within study communities. Research should therefore be directed at addressing this knowledge gap, by investigate malaria parasite dominance within mangrove mosquito populations, as well as vector behaviour under different mangrove ecological conditions. This would add value to these preliminary causal relationships uncovered and create an opportunity to further expand and solidify the evidence behind future causal inference enquiries. Environmental management aspects of the NMCP objectives must also consider integrated ecosystem management strategies that prevent mangrove land conversion, to eliminate potential vector breeding environments close to and within settlements.

Finally, instead of collating data at the district level, it would be useful to disaggregate hospital reported cases, DHS, and multiple indicator cluster survey data to reflect unique community characteristics of malaria experiences. Such regimes would make it easier to monitor and compare the distinct characteristics of contiguous ecosystems with the confirmed malaria cases within those specific communities. Additionally, it would facilitate better academic research. The information could simplify customisation of malaria risk reduction strategies to suit the specific needs of these communities, thus contributing to levelling out the unequal nature of risk and socio-economic burden of malaria in the country.

5.4.5 Concluding Comments

This study has presented QCA findings on the mangrove-related causal structure behind malaria incidence in Ghana's Volta Estuary, in a non-conventional approach to evaluating factors influencing malaria experience from a social ecological perspective. It has been demonstrated that health sector interventions alone do not deliver the most desirable malaria outcomes in Ghana's Volta Estuary region. Instead, conditions occasioned by ecological integrity improvements that accompany mangrove ecosystem interventions work in diverse ways to amplify the health benefits of public health interventions. This highlights the value of cross-sector approaches towards realisation of more sustainable, equitable and effective health and well-being aspirations within the most vulnerable ecosystems and populations. Based on the findings, specific policy customization actions have been proposed to exploit mangrove-related opportunities for better malaria management. Broadly, these actions involve increasing awareness about malaria risks of mangrove degradation and protecting the most vulnerable populations from these risks. Further suggestions relate to better data collection and monitoring for research purposes, building, and strengthening partnerships to meet some of the most elusive targets of Ghana's malaria management plan.

CHAPTER 6: MANGROVE AND MALARIA MANAGEMENT IN THE VOLTA ESTUARY: EVIDENCE, IMPLICATIONS AND POLICY OPPORTUNITIES

6.1 INTRODUCTION

Academic research in a variety of fields has demonstrated that human interaction with nature can deliver tangible physiological and psychological health benefits, which themselves can contribute towards greater wellbeing (Sandifer et al., 2015; Schröter et al., 2019; Marselle et al., 2021). Air and water purification, production and sustenance of biodiversity, diseases and climate regulation, detoxification and waste decomposition are some of the recognised health-impacting services provided by ecosystems (MA, 2005). Ecological systems worldwide are however being progressively altered by human-induced degradation, altering their capacities to supply ecosystem services vital for human health. Academics and policy makers are simultaneously uncovering stronger evidence linking services supplied by these ecological systems and human wellbeing (Sandifer et al., 2015). For some ecosystems and aspects of wellbeing, extensive knowledge and consensus exist, such as links between climate change, terrestrial forests, and economic needs of humans. The impacts of restoration on some urban natural spaces and their links to human wellbeing for example, has been investigated with respect to ecological integrity and social benefits (De Bell et al., 2020). On the other hand, knowledge related to neglected ecosystems such as those that supply marine and coastal ecosystem services (MCES) remains fragmented and sparse, despite being identified as crucial to human health by the Millennium Ecosystem Assessment (2005). In this context, the substantive focus of this thesis has been human-mangrove interactions and unexplored links with human health, focusing on how the nature of MCES supplied by mangroves shape malaria experiences.

This study investigated the human health-mangrove nexus; first in relation to how the states of mangrove ecosystems influence health experiences in general, and then more specifically, the incidence dynamics of the vector-borne disease malaria in Ghana. The goal for the research was to assess the impacts of mangrove ecosystem restoration on ecosystem services and the incidence of malaria, from the perspectives of people living close to mangroves of varying ecological states. Beside the incomplete science underpinning these phenomena, no work has been done to assess actual lived experiences according of mangrove dwellers themselves. Malaria was chosen as a useful indicator of ecosystem service-human health relationships because of uncertainties surrounding when and how deforestation influences prevalence of the disease in human populations (Bauhoff and Busch, 2018). As such, it was important in the study to shed light on the relevance of varieties of forest management to the control of the disease, which is also an endemic health concern in the tropical regions where mangroves are situated. The following research questions were addressed overall in this study:

RQ1. What are the current and potential health-related goods and services supplied by mangrove ecosystems as reported in the literature? (Investigated via a systematic literature review in Chapter 3)

RQ2. How have mangrove use and ecosystem states evolved alongside human health experiences in the case study location, and what difference does forest restoration make? (Investigated via key informant interviews in Chapter 4)

RQ3. What is the nature of the causal relationship between mangrove ecosystem integrity changes and malaria incidence characteristics within the study sites following interventions? (Investigated via assisted health questionnaires administered in mangrove communities, followed by QCA analysis in Chapter 5)

RQ4. What do mangrove ecosystem-related risk factors mean for current malaria and ecosystem management regimes in the region; and what are the policy advancement opportunities? (Presented as summary and implications of the study in Chapter 6)

Altogether, this analysis utilises three main tranches of research to investigate potential pathways for improving human health via ecosystem interventions, as summarised in Figure 46.

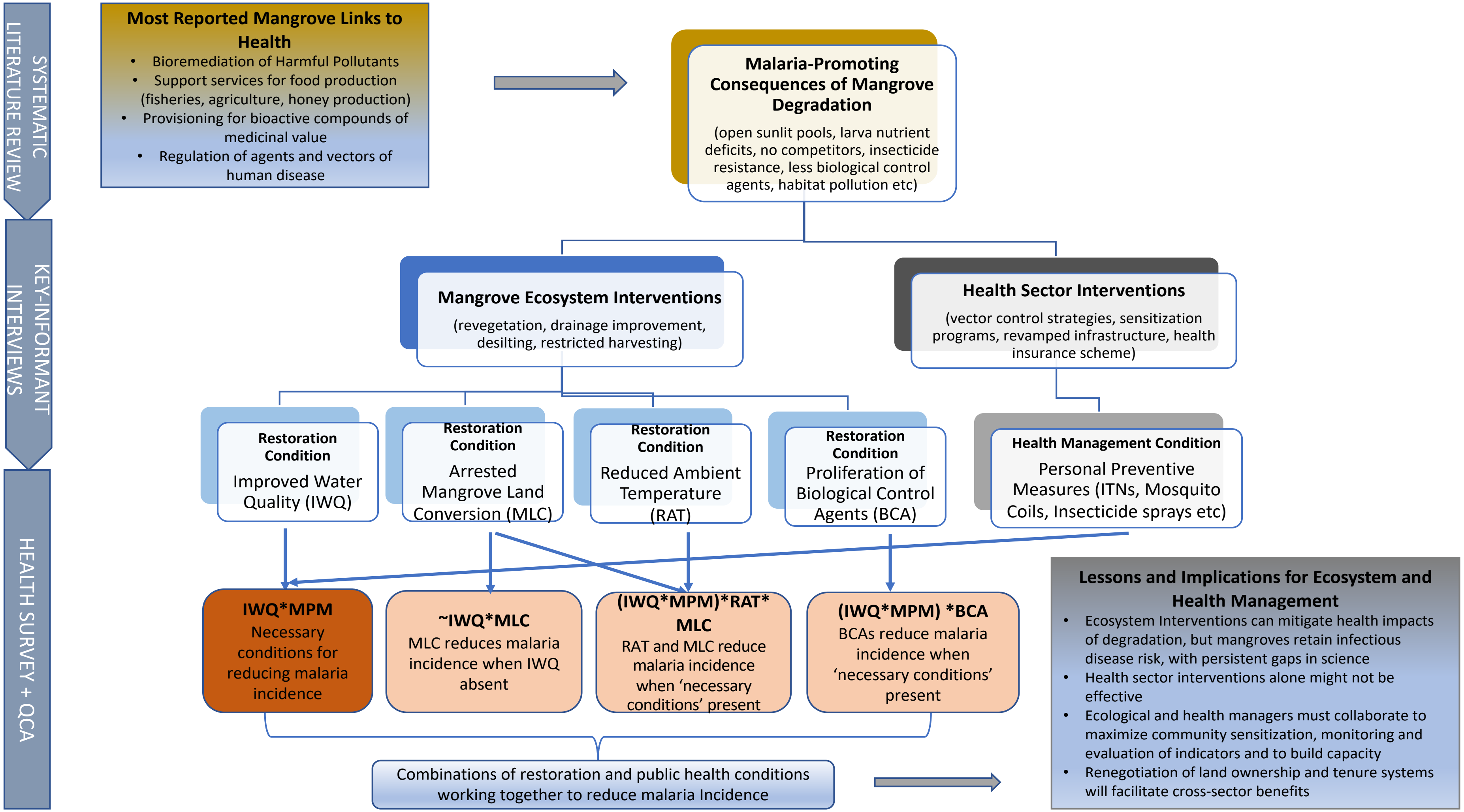

Figure 46: Summary of Research strategies, related findings, and implications

Firstly, reported academic evidence regarding mangrove-human health relationships was reviewed. The knowledge thereof was used to design a more targeted exploration of health-impacting dimensions of mangrove use and restoration in Ghana, as revealed through key informant perspectives. Thirdly, the role of mangrove ecosystem interventions in generating the ecological conditions that modulate malaria experiences in mangrove communities was investigated using QCA-facilitated causal inference analysis. Finally, drawing from the causal structure behind mangrove influence on malaria incidence, policy implications for optimising mangrove management, and lessening malaria and thus health risks in the most vulnerable societies, were explored. In essence, the research findings are summarized and used to evaluate current mangrove and malaria management strategies in Ghana. The discussion is extended to identify opportunities for policy enhancement, including lessons relevant to similar ecosystems and health management challenges in other locations. Overall, the study outcomes are useful additions to knowledge which enriches understanding of health and well-being management and contributes more broadly to sustainable ecosystem management towards an equitable future.

6.2 OVERVIEW OF RESEARCH FINDINGS

6.2.1 Key Finding 1: Mangroves Influence Human Health Outcomes Diversely (RQ1)

The first stage of this study consisted of a systematic review, which scrutinised the Web of Science Collection for research linking mangroves to various aspects of human health. After identification of 512 initial matching records, a series of screening steps including multiple eligibility criteria were applied, arriving at a final collection of 96 records subjected to content review. The most reported links to human health were: 1) provisioning and supporting services for medicinal supplies and food products, 2) bioremediation of pollution and 3) regulation of disease pathogens and vectors. Additionally, the findings of the systematic review reveal that in most cases, mangroves positively impact health aspects of wellbeing.

The evidence is stronger for some linkages and weaker for other aspects. Stronger evidence is particularly applicable to the in-vitro medicinal value of bioactives sourced from mangroves, and the collaborative role mangroves play, as part of wider connected marine and coastal ecosystems, in boosting human nutrition via fisheries support. Medicinal value was evident in mangrove endophytic fungi (Buatong et al., 2011), actinobacteria (Azman et al., 2017) as well as plant and plant associates (Patra et al., 2011). Antimicrobial, antifungal, antidiabetic actions were reported for extracts, alongside anti-inflammatory, anticancer, and antipyretic activities of varying strengths. Also uncovered as a positive impact was provisioning for fisheries via detritus production for food web support (Heithaus et al., 2011). Supporting ecosystem services for fisheries is more pronounced in mangroves when interconnectedness to related ecosystems such as coral reefs is optimal (Igulu et al., 2013), thereby sustaining all facets of fisheries life cycles. Mangroves have also been characterised as good bioremediators of environmental pollutants, facilitating various pathways of contaminant decomposition and biological exclusion (Aziz et al., 2018; Analuddin et al., 2017; Sandilyan and Kathiresan, 2014).

Knowledge gaps, on the other hand, manifest in underdeveloped theories surrounding regulation of infectious disease risk, and less widely reported evidence on the nutritional content of mangrove sourced food.

6.2.2 Key Finding 2: Time, Degradative Processes and Ecosystem Interventions Transform Mangroves and Associated Health Outlooks (RQ2)

With the information obtained from the systematic review, a second research phase using key informant interviews was designed. This research aspect involved experts in Ghana who provided insights regarding states and use of mangrove ecosystem resources in the country. A total of 14 key informants, comprising health management, media, academic, conservation and NGO experts were interviewed, to determine the extent to which systematic review findings apply to Ghana. Interviewees confirmed how mangroves have long been considered vital for coastal storm and flood protection, contributors to recreation and sense of place as well as sources of indispensable wood products, herbal medicine, and fisheries. For some communities, spiritual ties to the landscape are manifested in beliefs and superstitions around deities associated with this wetland type (Okeke, 2015; Darkwa and Smardon, 2010). The results further indicate how despite having undergone widespread degradation; Ghana's mangroves remain a significant part of the cultures of local communities. Further, loss of mangrove vegetation was linked to fisheries decline, to diminishing reliance on mangrove-sourced medicine, and pollution-related water quality deterioration. Recognition of weakening effects of degradative activities on benefits of mangrove wetlands was matched by appreciation among interviewed experts, of the importance of restorative practices in reinstating beneficial ecosystem services. For the purposes of this study, mangrove revegetation was conceptualised as an instigator of ecological restoration towards better 'ecosystem integrity', which was defined as:

> ***The progressive improvement in indicators symbolic of desirable ecosystem structure, organization, and functional traits as compared to variations of same indicators under degraded conditions.***

In addition to charting resident views about changes in ecosystem integrity traits, mangrove ecosystem services perceived to be linked to human health were also investigated in the key informant interviews. Interviewees emphasised the link between supporting ecosystem services for fisheries and human health. However, with respect to benefits of pollution remediation, the interviewees had limited knowledge. Acknowledgement of the impacts of restorative interventions was most pronounced in respect of how fisheries can be boosted following mangrove revegetation, especially in areas with longstanding community-based revegetation cultures. In other words, for communities engaged in active mangrove farming, they typically do so because they believe mangroves provide them with much larger fisheries harvests. It also emerged from the interviews that medicines have been sourced from mangroves in the past, yet use has declined significantly across all mangrove communities that were studied. Reference to mangrove medicines among key informants was only superficial and curiously vague. Interviewees attributed the rarity of mangrove medicinal resources today to formal health sector interventions, which have made 'western style' pharmaceuticals and healthcare services more widespread, although not uniformly rolled-out across rural and urban settings. While reports point to health care facilities and resources being more limited in rural than urban areas, there has been a shift towards greater reliance on these new services overall than on traditional medicinal knowledge. Apart from acknowledgement of the role of mangroves in trapping and filtering solid wastes from effluents, no tangible insights were proffered in respect of bioremediation of other forms of waste. Although revealed via the interviews that pollution is extensive in some mangrove environments, monitoring information was absent, making it difficult to estimate and compare remediation function of mangroves across sites. The link to infectious disease was reported as a disservice by respondents, who linked infectious disease risk for gastroenteritis and malaria to mangroves. According to health management key informants, mangrove areas report high incidences of diarrhoeal diseases such as cholera, in addition to the high malaria prevalence trait which is common across the country.

While insights from the key informants point to loss of some mangrove benefits e.g., medicinal goods being offset by recent developments such as better access to healthcare infrastructure and resources, some other benefits do not appear easily replaceable. For example, although reliance on mangrove medicines in Ghana's is not significant today, these resources could yet supply novel bioactive compounds that would otherwise be lost along with mangroves. Evidence from around the world clearly shows that these unique plants and their associates possess outstanding bioactive metabolites potentially relevant to future pharmaceutical breakthroughs. In a world where emerging infectious disease risk and antibiotic resistance are proving more difficult to handle, this intrinsic medicinal value of mangroves constitutes tangible impetus to halt and reverse degradation. What this implies in relation to the findings of this research is that efforts would be best directed at fashioning interventions in ways that preserve mangrove plant and plant associate biodiversity, as well as indigenous knowledge around their medicinal value. In Ghana, such a move would require a deliberate effort to collect and document knowledge of this nature from local mangrove folk, and subjecting claims around herbal products to bioassays. A metabolite characterisation process of this form could unearth useful alternative medicinal extracts capable of augmenting medicine availability and/or affordability shortfalls of health sector interventions. Further, such a validation exercise would provide a reliable framework for including certain species in mangrove revegetation projects, as well as for selecting species for conservation. It would additionally ensure indigenous information preservation that can survive dilution and loss over time, as a solution to knowledge decline concerns expressed by some key informants in CHAPTER 4.

Since interview responses suggest that comprehensive pollution monitoring in mangrove environments is not happening, research capital needs be directed at uncovering the ways in which Ghana's mangroves may be better managed to deliver the best pollution bioremediation outcomes. In doing so, an empirical basis for formulating protective laws and regulations, as well as for designing public education against consumption of the riskiest mangrove sourced food, can be obtained. By integrating findings of such investigations into planning for public health management, the reportedly pronounced infectious disease risk, as carried by ecological composition, and functioning of mangrove ecosystems, can be minimised.

6.2.3 Key Finding 3: Mangrove Ecosystem Interventions Combine Variedly to Amplify Benefits of Malaria Management Strategies (RQ3)

The final stage of the research comprised an assisted health survey processed using Qualitative Comparative Analysis (QCA). In this phase of the research, causal relationships between conditions promoted by mangrove restoration on one hand, and malaria incidence outcomes on the other, were investigated. Theoretical evidence incorporated into the conceptual framework shows that in degraded mangrove communities, deforestation increases sunlight penetration and thus temperatures, while facilitating stagnant water availability, which together are known to accelerate malaria vector lifecycles and biting rates (Reiter, 2008; Barreaux et al., 2018). Further, the biodiversity losses that accompany deforestation limit the availabilities of biological control agents capable of controlling vector populations (Muturi et al., 2008; Piyaratne et al., 2005). Lastly, the anthropogenic drivers of forested land conversion can exacerbate vector population dynamics and resistance to the most common insecticides used in vector control strategies (Ranson and Lissenden, 2016). Revegetation interventions have been theorised to, at the very least, initiate the process of overturning these malaria-aggravating characteristics as they relate to mangrove deforestation and degradation (Bosire et al., 2008; Crona and Rönnbäck, 2005; Walton et al., 2007). As such, temperature, water quality, presence of biological control agents and mangrove land conversion were the mangrove ecological conditions selected for direct interrogation in the QCA of participant responses. Additionally, the role of health sector interventions was integrated into the analysis, to examine their conjunctural impact on the malaria incidence dynamics alongside mangrove conditions.

Survey respondents residing near a mix of degraded, healthy, and restored mangroves were asked to recall their malaria experiences, alongside providing their observations surrounding the changes in mangrove ecological conditions over the past decade. Four mangrove communities and one non-mangrove community were surveyed. The responses from the mangrove communities were subjected to fuzzy set QCA software analysis. For the replanted mangrove communities, respondents were requested to assess changes in mangrove ecological conditions over time, by highlighting which ones have become more prominent following revegetation. For communities with healthy or degraded mangroves, they were simply asked to assess whether these conditions were absent or present. Using theoretical knowledge from the research literature and results of key informant interviews, the following specific conditions were identified and investigated as being consequential to mangrove ecosystem restoration, and of causal value to malaria incidence experiences:

1. Reduced Ambient Temperature (RAT)
2. Improved Water Quality (IWQ)
3. Presence of Biological Control Agents (BCA)
4. Arrested Mangrove Land Conversion (MLC)
5. Use of Malaria preventive Methods (MPM)

The QCA method was chosen to retain the depth and specificity advantage of the case study approach, while simultaneously facilitating cross-case comparison and generalization of the findings of the analysis. It was used to identify combinations of the mangrove ecological conditions listed (and abbreviated) above, and how they interact with malaria preventive measures to reduce incidence of the disease. As a causal inference technique, QCA is rooted in set theory, and interprets the outcome of interest based on whether cases that display that outcome belong to sets of the investigated conditions or not. The causal conditions above are theory-supported and identified by the researcher, who also determined thresholds for case assignment to condition and outcome sets of interest. This method is an alternative to traditional statistics and correlational theory, which is particularly useful for analysing how multiple factors interact asymmetrically and/conjuncturally to influence outcomes.

All participant cases were analysed by the fsQCA software to uncover the combinations of conditions whose presence (or absence) were most consistent in eliciting reported changes in malaria incidence over time. In the specific research scenario, the outcome of interest was a reduction in malaria incidence, which according to hospital data has declined by 47.3% and 49.2% respectively for the Ada East and Keta districts, from 2012 to 2019. Survey results showed that people living near healthier mangroves are more conscious of the ways in which they both use and ensure sustenance of these unique ecosystems. Results further revealed that people feel that malaria incidence has reduced over the past decade, a perception validated by the trends in confirmed malaria cases collated in hospitals in the area. The QCA results revealed the following salient Boolean combinations of restoration-related conditions and personal preventive measures working most consistently towards reduction in malaria incidence (* denotes combination, whereas ~ denotes absence of a condition). In other words, these 'solution terms' represent the QCA-generated pathways through which the investigated mangrove conditions combine with each other and/or with other personal interventions to reduce malaria incidence. Except for the 'necessary conditions', which applies to all communities, these causal recipes apply to different communities with different mangrove ecosystem characteristics but elicit the same malaria reduction outcome.

- **IWQ*MPM** – This solution term represents a combination of 'necessary conditions' for reducing malaria incidence. It shows that 'Improved water quality' and 'malaria preventive measures' (in the form of use of mosquito nets, coil, insecticide sprays etc.) must always be present together for malaria incidence reduction to occur.

- **~IWQ*MLC –** This solution term indicates that 'mangrove land conversion' (for other purposes such as agriculture and salt mining) must be arrested to reduce malaria incidence, when 'Improved water quality' (as defined by reduction of aquatic pollution) is absent.
- **(IWQ*MPM) *RAT*MLC** – This solution term demonstrates that 'reduced ambient temperature' and arrested 'mangrove land conversion' together, reduce malaria incidence when the 'necessary conditions' of 'improved water quality' and 'malaria preventive measures' are present.
- **(IWQ*MPM) *BCA** – This result shows that the presence of 'biological control agents' reduces malaria incidence when the 'necessary conditions' of 'improved water quality' and 'malaria preventive measures' are also present.

6.3 CONTRIBUTIONS AND IMPLICATIONS FOR RESEARCH AND POLICY (RQ4)

There is ample literature supporting the assertion that maintaining functional ecosystem biodiversity, in the form of individual traits of constituent species that work to sustain ecosystem processes, supports human welfare (Beaumont et al., 2007; Haines-Young and Potschin, 2010; Reich et al., 2012; Naeem et al., 2012; Loreau and De Mazancourt, 2013). These traits, according to Diaz et al., (2006), impact the way energy and matter are continuously circulated in ecosystems, thereby influencing the nature, quantity and quality of ecosystem services delivered. Thus, for degraded ecosystems, any interventions targeted at restoring biodiversity alongside abiotic factors to a more natural state will result in return and sustenance of wellbeing-enhancing services for humans. For mangroves, revegetation is seen as one such crucial intervention, instigating ecosystem recovery and thus delivery of services beneficial to humans (Saenger, 2013). This study has shown what the health enhancement pathways look like with respect to mangrove ecosystem interventions and malaria, one particular and important human health concern. The following sections of this chapter examine the significance of the contributions made by findings of this research for Ghana and in a wider global sense. Opportunities for policy and knowledge enhancement towards better environmental and health outcomes are also identified.

6.3.1 Livelihoods Diversification can Increase Local Fisheries Consumption and Improve Nutrition

Considering the results of this study in their entirety, the benefits of mangroves for health of contiguous human settlements are substantial. The mangrove ecosystem service most consistently linked to human health is support for fisheries, which interviewed experts widely acknowledged is enhanced following ecosystem restoration. Therefore, by intervening in degraded ecosystems, humans can derive a direct health benefit by way of more sustainable opportunities for better nutrition. Such interventions are even more vital given that Ghana is projected to experience a 20% climate-related decline in fisheries by 2050 as compared to 2000 levels (Golden et al., 2016). Moreover, overfishing, and inadequate dietary intakes impose malnutrition vulnerability in such areas where there is heavy reliance on fish for protein and micronutrients such as zinc and iron (Maire et al., 2021). As revealed by key informants, this direct dietary reliance on fisheries is further threatened when people are compelled by economic constraints to put up the best portions of the fisheries yields for sale instead of for their own household consumption. This implies that for the nutritional benefits of healthy fisheries to be maximised, there must be opportunities for adapting to climate impacts, for augmenting income from fisheries, and for providing alternative protein sources. Given that fishing is a dominant occupation in most of Ghana's mangrove communities (including study sites), this might be difficult to achieve without intentional livelihoods diversification initiatives. Fortunately, as revealed by conservation key informants, successful income-generating initiatives (such as training for beekeeping, soap-making, mushroom production skills etc) are not alien to mangrove restoration plans in Ghana. To eliminate the economic drivers of mangrove degradation, some sensitization and restoration projects in the past have included training activities for imparting such new skills for additional occupation options and sustainable livelihoods especially for women (See examples in Table 2 of CHAPTER 2). Improvement and replication of such livelihood enhancement models piloted by NGOs and donor agencies could offer alternatives that make it less imperative for fisherfolk to trade their best produce for income. This would increase the likelihood of local fisheries consumption to eliminate protein nutrition deficits, and to address child malnutrition as highlighted as a major concern by health experts.

Regarding how to reconcile global health and wellbeing improvements with the notion that degraded ecosystems diminish health (MA, 2005; Raudsepp-Hearne et al., 2010), the study findings provide a fresh perspective. Some of the outstanding debates about how to best guarantee equitable health are tied, for example, to the fact that child malnutrition remains a concern in marginal communities (Hosseinpoor et al., 2011), where lack of economic power limits alternatives available to the most vulnerable. In such communities, ecosystem contributions to the foundations of community nutrition could be crucial. This conclusion aligns with similar findings of Lachowycz and Jones (2014), to the effect that the mortality-reduction impacts of green spaces were most prominent in survey respondents from the most socio-economically deprived locations.

6.3.2 Wetlands Often Retain Infectious Disease Risk, but Gaps in Knowledge Persist

Ecosystems with adequate biodiversity to guarantee functionality are desirable for the purposes of supplying services that are beneficial to human health. Anthropogenic interferences with ecosystem functioning, which have been often destructive in the past few hundred years, continue to compromise the provision of health-supporting services. Provisioning for food, wood products, water along with the regulating services for disease control and cultural services for recreation and place-making continue to be undermined by both chronic and acute processes of ecosystem degradation. This emerging and critical situation has served as motivation for investigations into the health consequences of ecosystem disruption (Patz et al., 2008; O'Hara et al., 2000; Norris, 2004), and constituted part of the motivation for this study.

With respect to mangroves, the systematic review part of this study found that the pathways through which health disservices are manifested involve exposure to pathogens and vector organisms. In relation to Ghana specifically, an additional disservice was revealed by key informant interviewees to be potential exposure to toxic pollutants arising from unmonitored dumping of waste into mangrove environments. This was a significant finding, given that bioremediation of harmful pollutants was captured as a benefit of mangroves in the systematic review. However, it is also the case that people perceive mangrove-sourced products as potential source of toxic substances when waste discharges are unregulated.

Infectious disease risk associated with viral, pathogenic, and parasitic agents of infection, can inflict significant public health burdens. Especially for developing countries where population growth and resource scarcity undermine uniform, effective healthcare delivery, the value of ecosystem interventions that reduce this risk can be significant. However, in terms of the role of ecosystem biodiversity in modulating infectious disease risk, the evidence is weak and fragmented at present. In fact, the relationships foundational to disease outcomes are complex and, in some contexts, point to amplification rather than a reduction of risk (Wilson et al., 2000; Wood et al., 2017). For example, while anthropogenic environmental change can disrupt habitat structure in ways that eliminate certain nuisance arthropod species, other vector species like *Anopheles* might attain a competitive edge to thrive and spread malaria (Hough, 2014; Patz et al., 2000). Meanwhile, it is not clear if ecological restoration catalyses re-assembly of biodiversity well enough to level out prevalence of this same vector species. For vector-borne diseases in general, health impact investigations for ecosystem restoration are rare.

While ecosystem restoration rarely achieves a full turnaround in biodiversity loss, the literature reviewed in this report shows that some degree of improvement is achieved. In some instances, restoration is thought to be accompanied by ecosystem integrity improvements of up to 25% relative to degraded states. In other words, ecosystem services are revitalised following restoration, albeit to a lower level compared to fully thriving or intact ecosystems. Especially for restored wetlands ecosystems, Moreno-Mateos et al., (2012) report biogeochemical structure and functioning of between 23% to 26% lower than reference 'intact' ecosystems. This disparity between intact and degraded ecosystems raises questions about restoration impacts on biogeochemical functioning underpinning health-related ecosystems services, for which evidence is limited (Breed et al., 2021). For wetlands however, biodiversity benefits from restorative actions, are known to support aquatic life cycles of mosquitoes and pathogens. This signifies an exacerbation of risk for mosquito-borne infections and gastroenteritis for example, as confirmed by mangrove residents and health sector key informants.

Whatever the ecological integrity processes initiated by restoration actions such as revegetation, the eventual results are seldom comparable to original or pristine conditions. This is principally true for estuarine environments, where different revegetation and drainage realignment elements of restoration can produce different trajectories of ecological rehabilitation (Speldewinde et al., 2015). In this study, conclusions from both key informant interviews and health questionnaires show that mangrove sites are perceived to be reservoirs of insects that typically carry infectious disease risk. Furthermore, this risk is not perceived by research respondents to be lessened by impacts of ecosystem interventions, although no empirical basis has been established in support of such viewpoints. As such, it is important to analyse how ecological restoration of wetland ecosystems such as mangroves specifically impact the incidence of vector-borne diseases, within the context of the restoration approach used.

This study has revealed that targeted vector control strategies on their own may not be sufficient to deliver the most desirable disease incidence outcomes. This is evidenced by the fact that all the QCA causal recipes that most consistently lead to reduction malaria incidence involve malaria prevention measures working in conjunction with mangrove ecological conditions. How these vital ecological conditions affect malaria parasite prevalence and biting behaviour in mosquito vectors was not explored in this study and remain uncharacterised in respect of this present research context.

6.3.3 Ecosystem Interventions can Mitigate Some Health Risks of Degradation

From key informant evidence gathered for this study, the most significant health-related impact of mangrove interventions is support for nutrition, which in this context refers to access to better options for meeting protein and micronutrient needs in local diets. Specifically, better functioning mangrove ecosystems promoted by ecosystem interventions have been found to deliver improvements in fisheries supporting ecosystem services. This situation implies that focusing on more extensive mangrove restoration projects can positively impact protein nutrition for coastal dwellers, while also propping livelihoods related to the fishing and aquaculture industries. The resultant rise in income levels could empower residents to be able to afford a more diverse array of nutrition and healthcare options for a more wholesome health enhancement. Thus, the negative livelihoods and nutrition impacts of degradation can be effectively averted, with benefits potentially extending to non-mangrove communities that consume mangrove-sourced fisheries. In respect of impacts of interventions on mangrove bioremediation of pollutants, and on availability of mangrove medicinal products, the evidence generated in this study is weaker. Pollution monitoring is absent within mangrove lands, making comparisons with similar non-mangrove areas, or with acceptable contaminant thresholds used elsewhere, impossible. Therefore, the need for further investigations and risk evaluation lingers, especially because mangrove loss has been linked to fish contamination and health hazards in the Fosu Lagoon area (Bentum et al., 2011) of the country. Potentially, stronger links can be established by evaluating how revegetation modulates such risks.

Regarding infectious disease risk along the coast of Ghana, this study has shown that malaria incidence is modulated by revegetation-based mangrove ecosystem interventions. Mangrove restoration interventions that initiate the ecological conditions investigated in the causality analysis have been revealed to work in the conjunctural QCA-generated causal recipes to amplify the impacts of current vector-control strategies. Given the QCA results of this study, improved water quality, prevention of land conversion, reduction in temperature and biodiversity improvements that make biological control agents more abundant are some of the key conditions that must be targeted by restoration initiatives. These ecological conditions create the best environment for personal preventive measures to be most effective in reducing malaria incidence. This implies that these conditions are desirable for multiple reasons in respect of mangroves (and possibly similar ecosystem and infectious disease types), as they serve both environmental and health protection purposes.

6.3.4 Health Sector Interventions Alone do not Guarantee Optimal Health Outcomes

An overall key message that emerges from this study is that valuable opportunities exist for mangrove conservation efforts to be of value to health managers, implying there is a need for cross-sectoral collaboration to elicit the best possible benefits. At present, however, uncertainties surrounding the strength of the links between restoration and health outcomes, and the modest nature of measured ecosystem services returning after restoration, may obscure appreciation for such opportunities. In the current study, the solution coverage of less than 0.55 for the substantive QCA causal recipes demonstrates that those recipes only account for approximately 55% of malaria incidence reduction in the cases examined (See Table 28 of CHAPTER 5). From some perspectives, this might not constitute a robust enough indication of scalable, consistent, causation or a solid basis for health-ecology management interventions. Nevertheless, for communities where healthcare infrastructure and resources are stretched thin, the smallest opportunity to amplify benefits could still be useful. In those situations, the prospects that come with ecosystem restoration are particularly desirable, to the extent that they deliver additional benefits of livelihoods support while helping to meet wetland protection obligations. Extended to other types of ecosystems, benefits could additionally stretch into recreational and cultural advantages of ecosystem services improvement, which could be more vital to greater wellbeing than they presently are for Ghana’s mangroves. Given the current circumstances, mangrove degradation is damaging to human health and well-being. Therefore, any action that corrects the effects of degradation, without itself posing any health risks, is appropriate.

Not all interventions targeted at halting/reversing degradation can however be deemed equally desirable, based on the findings from this study. For example, in a mangrove community of Ghana where landowners frequently replant harvested mangroves, the general perception is that mosquitoes abound amongst the mangroves. While the plasmodium prevalence or biting behaviours of mosquitoes in those conditions have not been specifically studied, the implication is that in some situations stemming degradative processes can also preserve the conditions within which nuisance insects thrive. Thus, restoration designs that integrate additional strategies for minimising dangerous arthropod proliferation would be more ideal for similar ecological settings.

Such initiatives could include biologically safe larvicidal treatment of stagnant water bodies that pose the greatest risks, and targeted aquaculture of fish species that exert significant biological control effects over juvenile and adult arthropods. Additionally, indoor residual spraying, a malaria vector control strategy currently employed in the northern parts of the country, could be extended to communities near ecosystems thought to promote mosquito proliferation such as mangroves.

The study findings also suggest that health management professionals should work in a manner that augments the efforts of conservation practitioners. Policy formulation should consider, wherever possible, the alternative strategies for dealing with the shortfalls and inequalities in health delivery. For the communities where access to formal healthcare infrastructure is more strained, ecosystem restoration initiatives can and must be more strongly advocated for as a preventive measure against the most pressing health concerns. For example, in countries like Ghana where environmentally influenced infectious diseases like malaria and gastroenteritis are dominant, intervention types that concurrently provide pollution and vector control must feature more prominently in ecosystem management regimes. This is particularly important for wetland type ecosystems which have historical reputations as 'wastelands' and are thus less likely to be monitored for infectious disease risk. In Ghana, waste discharges into mangrove environments are not effectively monitored, and neither are their pollutant/contaminant levels measured for their health risks. To safeguard health in neighbouring populations, such scenarios must be turned around, especially because these locations happen to report troubling toxicity levels in fish (Bentum et al., 2011), and high incidences of gastroenteritis and malaria according to health sector interviewees. Pollution prevention as a targeted ecosystem intervention would minimise risk of exposure to toxic substances and coliform pathogens, thereby reducing disease burden to a level that can be better contained by the weaker public health management systems.

6.3.5 Ecosystem and Health Managers must Collaborate in Monitoring and Capacity Building

The role ecosystem degradation plays in magnifying public health problems makes it impossible to fully address health concerns without employing customized ecosystem management strategies. The work presented in chapter 5 uncovered some empirical causal relationships between conditions produced by mangrove revegetation and malaria incidence outcomes in neighbouring communities. This work contributes towards filling a research gap in the quest to redefine causal links between ecological restoration and human health in response to calls from the likes of (Breed et al., 2021). In that part of the study, perspectives from local communities in Ghana's Volta Estuary was used to map out the potential social-ecological processes influencing malaria incidence outcomes relative to mangrove ecosystem restoration. It was shown that while favourable health outcomes may not be necessarily assured, there are worthwhile synergies for public health and conservation experts to reorient policy towards more effective results. An interdisciplinary and collaborative approach that could facilitate such policy redesign is thus advocated.

Findings from key informants in this study show that an array of opportunities exists for mitigating health threats associated with environmental change. However, the situation is currently constrained due in some cases to limited resources, lack of empirical knowledge and insufficient stakeholder engagement and by-in. These circumstances must be addressed at the local level to inform appropriate policies that mitigate current health threats, and that build adaptive capacity to deal with unavoidable impending risks as well as prevent the emergence of new threats. These policies could be generated at the local, national, or international level depending on what the motivations and immediate targets are. Actors of both the health and environmental sectors must be collaboratively involved in rolling out strategies that sensitize the public about and instigate positive action regarding health risks posed by environmental change.

Some of the most striking key-informant commentary regarding mangrove benefits and protection in Ghana were related to diminishing local ecological knowledge. Respondents alluded to lack of interest among residents about medicinal ecological resources, arising from desires to relocate to other locations in future, and from a recent shift towards embracing formal healthcare interventions. For such people, sensitization programs could renew interest in safeguarding local ecological knowledge for a wider range of healthcare options.

Methodologies and procedures that effectively monitor trajectories of ecosystem service delivery following interventions could pave the way for detection and evaluation of opportunities for improvement. This applies to health interventions too, as the level of effectiveness will determine whether the right balance of impacts is being attained, especially for the most vulnerable populations. In this collection of research, QCA methodology has been used in part to define the most dominant causal relationships currently influencing malaria outcomes in Ghana's Volta estuary. However, these causal relationships are not exhaustive and furthermore are likely dynamic, given the uncertainties surrounding ecosystem processes and health management data. With continuous monitoring, such uncertainties may be minimised and pathways to superior delineation of ecological consequences and health experiences can be better predicted. QCA can remain a useful tool for an objective of this nature, as it provides the opportunity to test small to medium number of cases at a time, and to assess them based on varying combinations of experiences and environmental conditions. QCA parameters of fit additionally provide opportunities to assess the strength of causal relationships, to inform the design of strategies that amplify benefits of the most dominant and desirable causal recipe constituents.

6.3.6 Renegotiation of Mangrove Land Ownership and Tenure Systems would Facilitate Effective Ecosystem Interventions

Without clear ownership and authority, policy implementing agencies cannot implement the regulatory frameworks that limit or reverse degradative activities, especially those carried out outside protected areas. This position is reinforced by the views expressed by key informants to the effect that, where this is possible, legally mandated regulations instituted in line with the requirements of the Ramsar convention have yielded positive results. Further, landowners' demonstration of commitment to managing mangrove forests signals an opportunity for shared interests to be leveraged in negotiating favourable land tenure rights towards more impactful ecological interventions. Advocacy and lobbying for shared ownership rights for regulating agencies would make it easier for restoration programs to be rolled out, and for punitive and corrective measures to be applied in protecting those initiatives. At the same time, conservation experts would be enabled to sample and include indigenous knowledge into the planning of restoration programs to adapt them to local needs and acceptance requirements. In such scenarios, adequate compensation for relinquished land ownership rights would also imperative, making partnerships and project acceptance more easily attainable.

6.4 LIMITATIONS AND FUTURE RESEARCH RECOMMENDATIONS

In this research, ecological conditions arising from mangrove ecosystem interventions in Ghana's Volta estuary have been critically examined in respect of their contributions towards malaria experience in the location. This work has been conducted at a time when investigations into impacts on health aspects of wellbeing relative to wetland ecosystem interventions are rare in the academic space. Using a novel and innovative QCA methodology, this inquiry has revealed the most consistent causal pathways via which mangroves influence malaria outcomes in conjunction with a targeted health sector intervention. In effect, this undertaking has yielded causal recipes and inferences that were hitherto unexplored and thus unknown. The causal inferences thereof have been applied to broaden the conversation around how to potentially minimise infectious disease risk in a more efficient and equitable manner, by simultaneously addressing ecological underpinnings. Consequently, the results light a path to delivery of more desirable physiological health outcomes, while at the same time eliciting tangible environmental management goals. In relation to the subject matter holistically however, the findings of this study cannot be said to be exhaustive or immediately transferable to other environments or human health-ecology relationships.

Perspectives regarding psychological aspects of human health have not been surveyed as part of this research. This is attributable to the fact that the systematic review findings and key informant perspectives only captured mangrove links to physiological health. In general, some considerable knowledge however exists linking ‘natural environments’ with positive effects on mental health (Curtin, 2009; MacKerron and Mourato, 2013; Park et al., 2011; Song et al., 2014). De Bell et al., (2020) demonstrated how ecological benefits of river restoration made the location more appealing, thus positively impacting psychological health of visitors, despite concerns over cultural heritage loss. Some gaps persist nonetheless, regarding further research requirements in terms of empirical identification of the mechanisms accounting for these links, be it from an ecological perspective or otherwise (Dean et al., 2011).

Shortfalls exist for physiological diseases as well. For most disease clusters investigated by Maas et al., (2009) (Anxiety, asthma, depression etc), prevalence rates were lower in patients living within a 1km radius of green space, and higher for those living farther. Future investigations into impacts of ecosystem interventions on other types of diseases, as well as how involvement in restoration activities influence individual psychological and physical health experiences would also be insightful.

It is also worth noting that ecological conditions related directly to biodiversity within mangroves were not directly investigated in this study. This is partly because other scholarship, such as the review by Sandifer et al., (2015) found that infectious disease risk is probably not altered by biodiversity within an ecosystem, although they concede that this conclusion might vary. The authors further recommended deepening of the habitat destruction vs disease incidence conversion, in lieu of probing the biodiversity link, especially for specific diseases such as malaria. Thus, the scope of this research was not extended into biodiversity conditions of degraded or restored mangroves, focusing instead on vector habitat effects of restoration. Replicating this initiative by focusing on other ecosystems and diseases would be beneficial.

It had been an initial research objective to conduct some ecosystem observations and primary assessments to determine the different ecological conditions within the different mangrove forests. Some indicators of abiotic factors, ecosystem organization and ecosystem function had been selected for potential measurement and comparison across the ecosystems, to ascertain the different states of ‘ecosystem integrity’ as defined in Chapter 2. These indicators were 'total nitrogen and phosphorus’, foliage transparency, and indicator fish species diversity; which Lewis III, (2005) identified as relevant to estimation and evaluation of integrity in restored mangrove ecosystems. Measuring these parameters would have provided come empirical basis for estimating and comparing states of integrity across the mangroves bordering the sampled communities where present. It would have also afforded an extra avenue to validate the research participant perspectives expressed in respect of changes that have accompanied restorative interventions. However, resource and time constraints due to the Covid-19 pandemic made it impossible for these planned dimensions of the study to be explored, leading to that research objective being modified. Furthermore, the ecological managers of the Wildlife Division in Ghana unfortunately did not have any reliable long-term monitoring data analogous to these parameters either. Thus, this research had to rely solely on photographic details and participant reported ecosystem states, as well as indications presented in the reviewed literature, to conduct broad estimations of ecosystem ‘health.’ If the desired information had been available, stronger conclusions about degrees of ecosystem integrity across sampled sites would have been possible, in lieu of the estimations and assumptions that made about same.

Another missed research opportunity which could have enriched the findings of the QCA process, would have been the inclusion of additional ecosystem-related conditions that could have been analysed alongside health outcomes. These conditions were relative malaria parasite prevalence as well as biting behavioural differences amongst mangrove and non-mangrove mosquito vectors. Assessing whether mangrove mosquitoes carry similar parasite risk as non-mangrove mosquitoes or otherwise, or if their biting behaviours vary across landscape types, would have provided some valuable extra insights into how ecosystem interventions can influence parasite transmission. That information could have provided the opportunity to analyse the validity of assertions made by survey respondents and key informants, to the effect that mangrove mosquitoes do not transmit malaria. It would have further granted an avenue to test the condition of vector behavioural changes, which have been diversely theorised as forming a potential basis for malaria reduction in reforested ecosystems (Sattler et al., 2005; Lyimo and Takken, 1993; Takken et al., 1998).

Arguably, some degree of influence, apart from ecology of the surrounding environment, is exerted by the socio-economic circumstances prevailing in the communities under study, as posited by Hough, (2014). Such effects lie with social access to an improved healthcare delivery system, and fiscal empowerment to pursue alternative pathways to a healthier life (for example, to acquire orthodox pharmaceuticals, to diversify food options or to undertake exotic recreational activities etc). The need to decouple these socio-economic influences from causal relationships, or to investigate their impacts alongside those exerted by ecosystem services, was an important consideration in this research. By adopting the unconventional QCA methodology used in this study, both asymmetrical and conjunctural interplay of relationships eliciting the malaria outcomes reported have been explored. QCA methodology could thus be a useful tool for isolating ecosystem-related health impact assessments that hitherto had been fraught with uncertainties arising from other interloping influences. As a causal inference technique, it has been used successfully in solving confounding bias problems in other public health and environmental management scenarios.

Regarding the wider research arena, the success and associated outcomes of this research implies that QCA design and approach could help to improve the currently limited causal clarity in other studies that have sought to associate various aspects of health to conditions in diverse types of natural and green spaces. Fuller et al., (2007) for example, while concluding that habitat/species diversity and richness maximise health benefits of human contact with nature, were sceptical about the clarity of the causality connections that can be drawn. Hough (2014) expressed a similar concern about the lack of an effective way to conduct a causality analysis that isolates the role played by socio-economic conditions in the nature-health relationships. The use of QCA in this study has solved that problem by allowing the socio-economic condition of ‘personal preventive measures against malaria’ to be studied alongside mangrove-related conditions. Thus, both the individual causal role played by both types of conditions, as well as their conjunctural impact on the observed health outcomes have been integrated into the findings. QCA could thus be useful for future research of similar nature, to examine other socio-economic dimensions that were hitherto thought to mask the true impacts of green spaces on human health.

Finally, long-term institutional, ecological and health data monitoring and evaluation would be useful to for interdisciplinary research as a basis for future interventions in health and ecological management, particularly if made available for wider populations such as whole countries. This would provide valuable indicators and metrics testable against self-reported states of health, which are often most reliable if framed based on a short-term recollection period. Access to comprehensive, long-term monitoring data would provide more confident information for stronger causality analysis that would be more acceptable to research partners, donor agencies, and policymakers.

6.5 CONCLUDING REMARKS

This study adds to the body of knowledge on how pressures of urbanisation and industrialization seriously impact integrity of vital ecosystems, due to alterations produced by human activities such as waste disposal, agriculture, and other livelihood activities. Especially in poor and vulnerable societies, the health risks of pollution, vector habitat alterations and compromised food supply could be more serious because of the limited healthcare resources, solutions, and infrastructure available. At the same time, the promise of poverty alleviation via economic advancement activities makes industrialization and urbanization inevitable, especially in frontier economies such as Ghana. Comparably to Africa's poorest regions, climate change impacts on precipitation patterns, crop yields, infectious disease risk and extreme weather events are now predicted to further worsen the health consequences of degradative activities. For the most vulnerable societies and ecosystems, this skewed burden of disease and wellbeing makes remedial pathways vital. Approaches such as ecosystem restoration and adaptation strategies that minimise health risks in the first place could be lifesaving.

Elimination of health inequalities, including those of the UN Sustainable Development Goals, demands that health and environmental sector policies be co-aligned. Ecosystem-linked livelihood activities result in environmental degradation, which then limits health and wellbeing options available to the most marginalised societies. At the same time, these types of societies are the most likely to benefit directly from natural ecosystem services such as food provisioning, medicinal goods and recreational services that support population health. Unfortunately, while services of this nature diminish with environmental change, people who endure most of the resultant challenges do not have access to alternatives for meeting health needs. Health sector interventions including infrastructure, personnel, and access upgrades are crucial, especially under conditions of ecosystem degradation, but cannot stand alone. Unique social-ecological systems must be carefully balanced to yield optimal results, by aligning health sector interventions and targets to those of ecosystem preservation and management. This constitutes a reiteration of calls for multi-sectoral strategies for addressing human health and wellbeing targets (UNGA, 2015; Ford et al., 2015).

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APPENDICES

The following appendices have been redacted because they contain some personal and contact information:

APPENDIX A - PARTICIPANT INFORMATION SHEET

APPENDIX B - GENERAL PARTICIPANT CONSENT FORM

APPENDIX C - INTERVIEW CONSENT FORM

APPENDIX F – INTRODUCTION AND DATA REQUEST LETTER TO FORESTRY COMMISION, GHANA

APPENDIX G – DATA REQUEST AND RESEARCH PERMISSION LETTER TO GHANA HEALTH SERVICE

APPENDIX H – DATA REQUEST LETTER TO THE NATIONAL MALARIA PROGRAM

APPENDIX I – NATIONAL MALARIA PROGRAM DATA REQUEST APPROVAL (Keta-Anloga District)

APPENDIX J - NATIONAL MALARIA PROGRAM DATA REQUEST APPROVAL (Ada East District)

APPENDIX K – FORESTRY COMMISSION RESEARCH ASSISTANCE REQUEST APPROVAL II

APPENDIX L – FORESTRY COMMISSION RESEARCH ASSISTANCE REQUEST APPROVAL I

APPENDIX D - MANGROVE KEY INFORMANT INTERVIEW PLAN

INTRODUCTION OF THE INTERVIEWER		
Hello, my name is ____________________, and I will be conducting this interview as part of my academic research project at Lancaster University. During the interview, I would like to discuss the following topics: Your experiences with stakeholder participation in the mangrove replanting project(s); Impressions about ecological restoration, human health, and malaria vector influences; as well as the socio-economic impacts of mangrove management regimes.		
MANGROVE REPLANTING PROJECT		
Main questions	**Additional questions**	**Clarifying questions**
▪ Can you tell me about the mangrove project you worked on – whose initiative was it, and what were the objectives? ▪ Which other stakeholders were partners in the project	▪ What year was this undertaken, what was the duration? ▪ Why was it considered necessary? ▪ What circumstances contributed to its success (or otherwise) ▪ Was there community interest, participation, or support? What do you think accounted for this? ▪ Which strategies have been employed to ensure the sustainability of the restoration? ▪ What are some of the challenges you faced while implementing this project? ▪ How do you explain these problems? How could they have been avoided?	▪ Can you explain that point further? ▪ Is there anything else you can tell me about that? ▪ Can you give me some examples?
▪ In your estimation, what has the level of ecological enhancement been following the completion of the project? ▪ In your opinion, what are the most important of these enhancements?	▪ What are the most significant ecosystem improvements you have observed? ▪ Can you recount some of the specific interventions made to ensure the success of the project? ▪ Would you conclude that the ecosystem is capable of self-sustenance without further intervention?	

<table>
<tr><td></td><td>When you consider mosquito populations within the ecosystems, how do you think that has been affected following the project.
What about biodiversity revival in general? Have there been any impacts on that?
Do you have any comments on the status of known mosquito larvae or adult predator species within the project sites?</td><td></td></tr>
<tr><td colspan="3">ASSESSMENT OF IMPACTS</td></tr>
<tr><td>Main questions</td><td>Additional questions</td><td>Clarifying questions</td></tr>
<tr><td>Were there any restrictions placed in the site in terms of how the mangrove resources can be exploited?</td><td>If so, what were the alternative options offered to the nearby residents to make up for the potential livelihood losses?
In your opinion, how satisfied are the people living nearby about current mangrove management strategies?
Are there any widespread lifestyle shifts that have occurred to accommodate the sustainability of the project?
Do you believe that well-being has been impacted in any way by this project(s)?</td><td rowspan="3">Can you explain that point further?
Is there anything else you can tell me about that?
Can you give me some examples?</td></tr>
<tr><td>CONCLUSION OF INTERVIEW</td><td rowspan="2"></td></tr>
<tr><td>Are there any other comments you want to make about your experiences with the project(s)?
Are there any other persons you could introduce me to who could be of any help with my research now or in the future?</td></tr>
</table>

THANK YOU FOR YOUR TIME

APPENDIX E - MALARIA KEY INFORMANT INTERVIEW PLAN

<table>
<tr><td colspan="3">INTRODUCTION OF THE INTERVIEWER</td></tr>
<tr><td colspan="3">Hello, my name is ____________________, and I will be conducting this interview as part of my academic research project at Lancaster University.

During the interview, I would like to discuss the following topics: Your experiences with stakeholder contribution to the malaria management programme(s); Impressions about the nature of control of the disease in the location(s) of interest; as well as the socio-economic impacts of current changes in incidence rates of the disease.</td></tr>
<tr><td colspan="3">NATIONAL MALARIA CONTROL PROGRAMME</td></tr>
<tr><td>Main questions</td><td>Additional questions</td><td>Clarifying questions</td></tr>
<tr><td>▪ Can you tell me about the malaria projects you work on – whose initiative is it, and what are the objectives?
▪ Which other stakeholders were partners in the project</td><td>▪ How long has the current malaria programme been in force?
▪ Why was it considered necessary?
▪ What are the specific actions of intervention implemented so far?
▪ What circumstances contribute to its success (or otherwise)
▪ Apart from government intervention (e.g., subsidization of ITNs, IRS etc.), what has the nature of community interest, participation or support been? What do you think accounted for this?
▪ Which strategies have been employed by government through the ministry to ensure the sustainability of the programme?
▪ What are some of the challenges you face with implementation of this programme?
▪ How do you explain the reasons behind these problems? How could they have been avoided?</td><td rowspan="2">▪ Can you explain that point further?
▪ Is there anything else you can tell me about that?
▪ Can you give me some examples?</td></tr>
<tr><td>▪ In your estimation, what has the extent of health enhancement been following the initiation of the programme?</td><td>▪ What are the most significant improvements you have observed, and in which areas? (Prevention, treatment, mortality rates etc.)</td></tr>
</table>

<table>
<tr>
<td>In your opinion, what are the most important of these enhancements?</td>
<td>Can you recount some of the specific strategies put in place to ensure the success of the initiative?
Would you conclude that the objectives of the programme are being achieved?
When you consider mosquito populations within the locations in question, would you say a certain trend has emerged in this regard?
What would you say has contributed to such a trend?
Do you have any comments on the status of mosquito vector breeding environments in the area?</td>
<td></td>
</tr>
<tr>
<td colspan="3">ASSESSMENT OF IMPACTS</td>
</tr>
<tr>
<td>Main questions</td>
<td>Additional questions</td>
<td>Clarifying questions</td>
</tr>
<tr>
<td>Do livelihoods-related motivations exist for the malaria control programmes, or were they all health based?</td>
<td>If so, what were the specific socio-economic effects of malaria that were targeted for elimination?
In your opinion, how satisfied are the people in terms of the effects of current malaria prevalence rates on their livelihoods?
Are there any widespread lifestyle and livelihood shifts that have occurred that are attributable to malaria management regimes today?
Do you believe that well-being has been impacted in any way by this programme(s)?</td>
<td rowspan="3">Can you explain that point further?
Is there anything else you can tell me about that?
Can you give me some examples?</td>
</tr>
<tr>
<td>CONCLUSION OF INTERVIEW</td>
<td rowspan="2"></td>
</tr>
<tr>
<td>Are there any other comments you want to make about your experiences with the programme?
Are there any other persons you could introduce me to who could be of any help with my research now or in the future?</td>
</tr>
</table>

THANK YOU FOR YOUR TIME

APPENDIX M – ASSISTED HEALTH QUESTIONNAIRE

Health Questionnaire

Instructions

This is an academic research questionnaire that explores perceptions about mangrove forests and malaria incidence. Refer to the attached participant information sheet before consenting to complete all sections. Answer questions as they relate to you. For most answers, check the box(es) most applicable to you or fill in the blanks.

Section A - About You

1. Your Age

(Select only one)

- ☐ 30-40
- ☐ 41-50
- ☐ 51-60
- ☐ 61-70

2. Your Gender

(Select only one)

- ☐ Female
- ☐ Male
- ☐ Other

3. Your Occupation

(Select all that apply)

- ☐ Farmer
- ☐ Fisherman
- ☐ Petty Trader
- ☐ Other

4. Formal Education

- ☐ None
- ☐ Primary/Elementary School
- ☐ Secondary School
- ☐ Tertiary
- ☐ Other

5. Marital Status

- ☐ Single
- ☐ Married
- ☐ Widowed
- ☐ Divorced

6. How long have you lived in this community?

- ☐ 1-5 yrs.
- ☐ 6-10 yrs.
- ☐ 10-15 yrs.
- ☐ 15-20 yrs.
- ☐ Over 20 yrs.

7. How much time in a year do you spend in this community?

- ☐ All the time
- ☐ 9-12 months
- ☐ 6-9 months
- ☐ 3-6 months
- ☐ 0-3 months

Section B - About the Mangrove Forests

1. Do you or anyone in your family use nearby mangrove resources?

- ☐ Yes
- ☐ No (Go to 5)
- ☐ Not anymore

Reason:

2. How do you use mangrove resources?

- ☐ Wood products (domestic use)
- ☐ Wood products (commercial use)
- ☐ Fishing
- ☐ Hunting
- ☐ Crabs and mollusks
- ☐ Other Forest products
- ☐ Other

3. How Often do You Use Mangrove Resources?

- ☐ Everyday
- ☐ 2-3 times a week
- ☐ Once a week
- ☐ Once a month
- ☐ Occasionally

4. Some replanting has been done in the nearby mangrove forests. Have you had access since then?

- ☐ Yes, but not as often as before
- ☐ Yes, as often as before
- ☐ Yes, more than before
- ☐ No, not at all

Reason:

5. What kinds of changes do you think have happened in the mangrove forest since the replanting?

(Select all that apply)

- ☐ Thicker forest canopy
- ☐ Cooler Temperatures
- ☐ Increased fish quantities
- ☐ Increased crustacean and mollusk numbers
- ☐ Increased mosquito abundance
- ☐ Reduced mosquito abundance
- ☐ Increased insect abundance
- ☐ Increased wildlife abundance
- ☐ Better storm/flood protection
- ☐ Improved water quality
- ☐ No changes
- ☐ Other

6. In general, what are your feelings about the effects of the replanting on both your personal and community wellbeing?

Section C - About your Experiences with Malaria

1. What symptoms do you consider to be indicative of malaria?

(Select all that apply)
- ☐ Elevated body temperature
- ☐ Joint aches/pains
- ☐ Bitter taste in mouth
- ☐ Shivering and sweating
- ☐ Vomiting
- ☐ Dizziness (vertigo/confusion)
- ☐ Convulsions
- ☐ Other

2. When last did you or any member of your household show any of these symptoms?

(Select all that apply)
- ☐ Never
- ☐ Less than a week ago
- ☐ Within the last month
- ☐ Within the last year
- ☐ 1 to 5yrs. ago
- ☐ Over 5 years ago
- ☐ Cannot recall

8. At what times/periods/seasons are these symptoms more common?
- ☐ Throughout the year
- ☐ Rainy seasons
- ☐ Dry season
- ☐ Other

3. What steps do you take to treat a suspected malaria episode?

(Select all that apply)
- ☐ Use local herbal treatments only
- ☐ Use herbs first, then go to hospital
- ☐ Go to hospital for treatment
- ☐ Other

4. If you had to go to the hospital for malaria treatment, which one are you most likely to go to?
- ☐ Nearest district health center
- ☐ Other

5. What is your understanding of conditions that cause malaria?

(Select all that apply)
- ☐ Bad Sanitation
- ☐ Bad water
- ☐ Weedy Surroundings
- ☐ Bad food
- ☐ Exposure to intense sunlight
- ☐ Mosquito bites
- ☐ Other

6. Do you and your household take any steps to protect yourself from malaria?
- ☐ Yes, always
- ☐ Yes, sometimes
- ☐ No, never (Go to 8)

7. What are the preventive steps you take against malaria?

(Select all that apply)
- ☐ Insecticide treated net
- ☐ Mosquito coil
- ☐ Insecticide sprays
- ☐ Use of 'prophylactic indigenous herbs'
- ☐ Use of prophylactic hospital drugs
- ☐ Wearing protective clothing
- ☐ Other

8. Do all members of your household have access to these preventive measures?
- ☐ Yes
- ☐ No

Reason:

9. What has your family's experience with malaria been over the past few years?
- ☐ Moderate increase in incidence
- ☐ Significant increase in incidence
- ☐ No change
- ☐ Moderate decrease in incidence
- ☐ Significant decrease in incidence
- ☐ No incident in years
- ☐ Cannot remember
- ☐ Other

10. In general, in what ways do you think malaria affects your personal, family and community wellbeing?

11. Is there any other information you would like to share with me?

Thank you very much for your time

APPENDIX N – Priority programme areas, including some specific objectives of the Ghana National Malaria Control Programme (NMCP 2014-2020)

GOAL : Strengthen Health Systems Through

1. **Prevention**
    - 100% of households will own at least one Insecticide Treated Net (ITN)
    - 80% of the general population will sleep under ITNs
    - Increase the number of children under-five and pregnant women sleeping under treated net from current levels to 85%
    - 100% of the pregnant women shall be on appropriate Intermittent Preventive Treatment and receive at least two doses
    - 90% of all structures in targeted districts will be covered through Indoor Residual Spraying (IRS)
2. **Diagnosis and Treatment**
    - 90% of all patients with uncomplicated malaria will be correctly managed at health facilities using Artemisinin-based Combination Therapy (ACTs)
    - 100% of health facilities will provide prompt and effective treatment using (ACTs)
    - 100% of communities will have access to community-based treatment for uncomplicated malaria
    - 90% of caretakers and parents will be able to recognize early symptoms and signs of malaria
    - 90% of children under five years of age with fever will receive an appropriate ACT within 24 hours of onset
3. **Surveillance, Monitoring and Evaluation**
    - Routine Health Information Management and Data Quality Audits
    - Ongoing Research and Household Surveys
    - To strengthen and maintain the capacity for program management, partnership, and coordination to achieve malaria programmatic objectives at all levels of the health care system
    - To increase awareness and knowledge of the entire population on malaria prevention and control to improve uptake and correct use of all interventions.