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People and the intertidal

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Environmental and Marine Biology
Department of Biosciences
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AUTHOR'S CONTACT INFORMATION
Lina Mtwana Nordlund
Environmental and Marine Biology
Department of Biosciences
Åbo Akademi University
BioCity, Artillerigatan 6
FI-20520 Åbo, Finland
linanordlund@gmail.com

SUPERVISOR
Docent Johan Erlandsson
ARONIA Coastal Zone Research Team
Åbo Akademi University / Novia University of Applied Sciences
FI-10600 Ekenäs, Finland
Present address: Vattenmyndigheten Västerhavet
Länsstyrelsen i Västra Götalands län
SE-403 40 Göteborg, Sweden

SUPERVISOR
Docent Martin Gullström
Department of Systems Ecology
Stockholm University
SE-106 91 Stockholm, Sweden

EXAMINER
Professor Erik Bonsdorff
Environmental and Marine Biology
Åbo Akademi University
FI-20520 Åbo, Finland

REVIEWER
Professor Marianne Holmer
Institute of Biology
University of Southern Denmark
DK-5230 Odense M, Denmark

REVIEWER
Docent Michael Tedengren
Department of Systems Ecology
Stockholm University
SE-106 91 Stockholm, Sweden

OPPONENT
Professor Sven Beer
Department of Plant Sciences
Tel Aviv University
IL-69978 Tel Aviv, Israel

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Cover photo: Invertebrate harvester in Zanzibar. Photo: Lina Mtwana Nordlund

A FEW WORDS…

I did it! Endless power cuts, internet failure, no shows, and struggles, but I did it and I loved it!

I sincerely hope that my work can contribute to a more sustainable future.

To all of you that have been there in my life, helped me with this thesis or in other ways, this is for you.

Women on their way out to harvest
invertebrates in Zanzibar, Tanzania.
Photo: Lina Mtwana Nordlund

Abstract

The intertidal zone in the Western Indian Ocean (WIO) provides several important ecosystem services, but the intertidal is experiencing an accelerating loss of habitats and biodiversity, due to among other factors, an increasing human population, overexploitation of resources, poverty and the pressures of economic development. The major aim of this thesis was to achieve a better understanding of the intertidal zone in the tropical and subtropical WIO. The specific objectives were to examine the intertidal zone, investigate how human induced changes affect biodiversity and in turn local livelihood, as well as to assess potential sustainable management strategies.

Paper I provides an overview of the state of and pressure on the intertidal area in the WIO (from experts' opinions) and concludes that there is a lack of research, monitoring and management as well as understanding of the intertidal zone in the WIO. It also provides suggestions of possible management strategies to improve the situation of human dominated and overexploited intertidal ecosystems. **Papers II** and **III** show clear negative biological and ecological effects of invertebrate harvesting (gleaning/ collection of e.g. molluscs) and harbour activities. **Paper III** describes the general fishing strategy among local women and their opinion that both seagrass habitats and diversity/abundance of associated invertebrate species have decreased during the last decade, as well as the attempt to understand social-ecological processes of invertebrate harvesting and the subsequent biodiversity loss, including major negative effects on livelihood and income. **Paper IV** shows that remote sensing can be used to estimate intertidal habitat distribution and seagrass biomass even in challenging patchy multi species environments, and that this approach has a clear potential as a monitoring tool for large intertidal areas of the WIO.

The thesis concludes that there is a low formal understanding of most ecosystems in the intertidal zone of the WIO, and thus this environment receives very little attention and is not prioritized for research, monitoring and management. The low formal understanding also leads to unregulated use in several of the systems, which can cause negative effects and impacts on biodiversity, local people's economy and livelihood. Therefore, increased research and monitoring as well as improved management and conservation of the intertidal zone in the WIO are urgently needed.

Keywords: Intertidal zone, Biodiversity, Human exploitation, Invertebrate harvesting, Social-ecological systems, Multidisciplinary, Local livelihood, Sustainability, Ecosystem management, Monitoring, Seagrass, *Thalassodendron ciliatum,* Western Indian Ocean, Zanzibar, Inhaca Island

Sammanfattning på svenska – Summary in Swedish

Människan är beroende av naturens varor och tjänster såsom vatten, fisk och solljus. Med en ökande befolkning i kustnära områden ökar exploateringen vilket i sin tur hotar våra kustekosystem. Tidvattenzonen är den del av kustzonen där hav och land möts. I västra Indiska oceanen (VIO) är nivåskillnaderna på tidvatten vid vårflod 0.4-6 m beroende på var i regionen man befinner sig. De allra flesta områden i regionen har två högvattenperioder respektive två lågvattenperioder per dygn. I områden där bottentopografin är plan kan tidvattenzonen sträcka sig flera kilometer. Tidvattenzonen är en miljö i ständig förändring som ibland täckt med vatten och ibland är torrlagd, vilket gör att bland annat temperaturskillnaderna kan bli väldigt stora. Tidvattenzonen omfattar många olika naturtyper (habitat) som t.ex. sandstränder, mangroveskogar, sjögräsängar, laguner, algbäddar och klippstränder, där alla är mer eller mindre hotade. De största hoten mot tidvattenzonen är relaterade till överexploatering av naturresurser och inkluderar t.ex. avverkning av mangroveskogar, fiske av olika slag och plockning av musslor, bläckfisk, sjögurkor, etc. Hoten ökar ständigt som en konsekvens av överbefolkning, fattigdom och illa planerad bebyggelse vid kusten.

I denna avhandling har sjögräsängar fått en viktig roll eftersom de utgör ett värdefullt, artrikt och individtätt ekosystem med stor utbredning i tidvattenzonen i hela VIO. Sjögräsängar förser människor i området med många viktiga varor och tjänster såsom till exempel fiskemöjligheter och skydd mot stora vågor, men fyller även viktiga funktioner för andra organismer genom att förse dem med mat och skydd mot fiender (predatorer) samt fungera som barnkammarhabitat. I takt med ökad exploatering har utbredningen av sjögräs minskat drastiskt runt om i världen, inklusive VIO.

Syftet med min avhandling är att öka förståelsen för tidvattenzonen i tropiska och subtropiska västra Indiska oceanen. Detta har gjorts genom att: (1) analysera olika habitat och deras biologiska och ekonomiska värden, hot, pågående forskning, miljöövervakning och förvaltning samt ge förslag till framtida förbättringar (studie I), (2) undersöka effekterna av mänsklig påverkan, med fokus på hamnaktiviteter och ett oreglerat fiske i form av plockning av ryggradslösa djur (skaldjur m.m.) (studie II och III), (3) undersöka hur plockning av ryggradslösa djur påverkar ekonomin och

samhället hos lokalbefolkningen (studie III), (4) identifiera, värdera och diskutera möjliga förvaltningsstrategier för tidvattenzonen (studie I), och (5) testa en potentiell miljöövervakningsmetod (fjärranalys) för att öka kunskapen om utbredningen av habitat och uppskatta sjögräsbiomassa (studie IV). I avhandlingsarbetet har jag använt mig av ett multidisciplinärt tillvägagångssätt och baserat studierna på ekologisk och biologisk provtagning, intervjuer, observationer, diskussionsgrupper, frågeformulär och fjärranalys.

I den första delen av studie I har jag undersökt tillståndet hos tidvattenzonens ekosystem/habitat med hjälp av ett frågeformulär och diskussioner med sakkunniga i regionen, d.v.s. personer som arbetar med forskning och/eller förvaltning av tidvattenzonen i VIO. Resultatet visar att det finns flera viktiga habitat i tidvattenzonen och många värden, t.ex. stränder som attraherar turister och lokalbefolkning för rekreation, habitat som skyddar kusten mot erosion, fisk och skaldjur, träd för byggnadsmaterial etc. Tyvärr finns det också många hot som kan slå hårt mot tidvattenzonen, såväl från land som från hav. Svaren från de sakkunniga visar att det endast finns mycket lite forskning kopplad till tidvattenzonen i VIO och att det bara är mangrovesystem och artinventeringar som har en relativt god forskningsstatus. Flera habitat och regioner saknar helt forskning och har liten eller ingen miljöövervakning. Man vet helt enkelt inte hur statusen är för flera av resurserna i tidvattenzonen i VIO. De sakunniga betonar även att tidvattenzonen ofta saknar förvaltning. Tidvattenzonen, eller delar av denna zon, är ibland inkluderade i större nationalparker eller reservat, men saknar nästan alltid specifik förvaltning. Vissa mangroveskogar är direkt skyddade, men generellt är det väldigt lite förvaltning i tidvattenzonen. Vidare påpekas att det behövs mer kunskap och uppmärksamhet kring tidvattenzonen.

Studierna II och III visar att sjögräsområden med hamnaktiviteter och områden där ryggradslösa djur (såsom musslor) plockas har en mycket lägre artrikedom, individtäthet och biomassa av dessa ryggradslösa djur jämfört med skyddade eller avlägsna sjögräsområden. Studie III visar även att det är mest kvinnor och barn som plockar ryggradslösa djur och att de föredrar sjögräs som plockningsområde. De intervjuade personerna rapporterade att sjögräsutbredningen samt storleken och individtätheten hos ryggradslösa djur har minskat under de senaste decennierna. Anledningen till detta är troligen att antalet personer som är involverade i plockningen har ökat under de sista decennierna samt att det förekommer en viss grad av oförsiktighet när man plockar och att man plockar allt mindre djur. Att plocka ryggradslösa djur är en viktig aktivitet för kvinnorna i regionen, framförallt för att samla mat till familjen, men i vissa fall också för att sälja delar av sin fångst och på så sätt förbättra eller skapa sig en inkomst.

I den andra delen av studie I har sakkunniga i VIO tagit ställning till hur viktiga och genomförbara olika föreslagna förvaltningsmetoder är samt hur stort förtroende de har för dessa metoder. De metoder som rankades som viktigast var att: (1) utveckla en integrerad kustzonsförvaltning med lokalbefolkningen, (2) forska på viktiga arter och deras relation till ekosystemet, (3) genomföra upplysningskampanjer och utbildningsprogram, (4) temporala och rumsliga förbudszoner, och (5) etablera förbudszoner i överutnyttjade områden tillsammans med lokalbefolkningen. Resultat från studien ger anvisningar om hur man kan gå vidare för att skapa ett mer hållbart nyttjande av tidvattenzonen.

I studie IV testades fjärranalys som en metod för att beskriva habitatutbredning i den grunda tidvattenzonen samt möjligheten att uppskatta biomassa för olika sjögräsarter. Denna information är väldigt viktig för att effektivisera miljöövervakningen av grunda områden i regionen och därtill kunna mäta och följa förändringar i utbredningen och biomassa av tidvattenzonens habitat. Vi använde oss av IKONOS-bilder med 4 x 4 meters upplösning. Habitatutbredningskartan visade på hög kvalitet då kartläggningen av sjögräs stämde till 93.5%. Kartläggningen av sjögräsbiomassa fungerade också bra för de kortare sjögräsarterna och biomassan var korrekt kartlagd till 83%. För det längre sjögräset som växer på stam var biomassan korrekt kartlagd till 57%. Modernare satellitbilder med högre upplösning skulle möjligen kunna skilja de olika sjögräsarterna åt och på så vis förbättra kartläggningen. Resultaten visar att fjärranalys med fördel kan användas för att kartlägga och uppskatta sjögräsbiomassa i tidvattenzonen inom VIO-region.

Sammanfattningsvis visar denna avhandling att det finns ett stort värde i den komplexa tidvattenzonen, men området hotas från både land och hav, genom t.ex. erosion och föroreningar. Uttnyttjandet av kustzonen är stort och aktiviteter såsom fiske i form av plocking av musslor och andra ryggradslösa djur och hamnaktiviteter påverkar biodiversiteten negativt, vilket leder till försämrad levnadsstandard för resursutnyttjarna. För att förbättra situationen krävs det mer forskning, miljöövervakning samt bättre förvaltning av tidvattenzonen i VIO. De sakunniga har rangordnat flera genomtänkta förslag (redovisat i studie I) på hur man skulle kunna förbättra miljön i tidvattenzonen och skapa ett mer hållbart nyttjande och dessa borde testas på ett adaptivt sätt. Fjärranalys är en potentiell metod för en storskalig miljöövervakning.

Resultaten presenterade i denna avhandling ger en ökad kunskap om tidvattenzonen i utvecklingsländerna inom VIO-regionen som kan användas för att initiera och fortsätta att utveckla hållbara förvaltningsstrategier av biologiska resurser.

Nyckelord: Tidvattenzon, Biodiversitet, Fiske, Plockning av ryggradslösa djur, Mänsklig påverkan, Exploatering, Sjögräs, Förvaltning, Hållbar utveckling, Multidisciplinär vetenskap, Miljöövervakning, Västra Indiska Oceanen, Tanzania, Zanzibar, Moçambique, Inhaca Island

List of papers

This thesis is based on the following papers, referred to by their roman numerals:

I Nordlund LM, de la Torre-Castro M, Erlandsson J, Jiddawi N, Muthiga N, Conand C, Gullström M. Intertidal management in the Western Indian Ocean – current status and future possibilities. Submitted to Conservation Biology.

II Nordlund LM, Gullström M. Substantial biodiversity loss in seagrass meadows influenced by local invertebrate fisheries and harbour activities. Submitted to Biodiversity and Conservation.

III Nordlund L, Erlandsson J, de la Torre-Castro M, Jiddawi N. 2010. Changes in an East African social-ecological seagrass system: invertebrate harvesting affecting species composition and local livelihood. Aquatic Living Resources 23: 399-416

IV Knudby A, Nordlund L. 2011. Remote sensing of seagrasses in a patchy multi-species environment. International Journal of Remote Sensing 32: 2227-2244

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My contribution: Predominantly responsible for Papers I, II and III, including planning, all field work, analyses and writings. Paper IV was initiated in collaboration with my co-author (A. Knudby). I was responsible for all seagrass related work. The study was designed and written together with A. Knudby. The remote sensing analysis was done by A. Knudby.

Other related work:

Nordlund L, de la Torre-Castro M, Jiddawi N, Erlandsson J. 2011a. Socio-ecological effects from invertebrate harvesting in Tanzanian seagrass ecosystems – the need to investigate management approaches and future possibilities. 2nd Annual Agricultural Research Review Workshop 2010. Conference proceeding.

Nordlund L, Langjahr K, Walther A. 2011b. Chumbe Island Coral Park education programme – communicating environmental issues. 2nd Annual Agricultural Research Review Workshop 2010. Conference proceeding.

Nordlund ML, Kloiber U, Carter E, Riedmiller S. Chumbe Island Coral Park – Governance Analysis. Marine Policy, in review.

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Abbreviations

DPSIR	Driving forces – Pressures – State – Impact – Responses
EEA	European Environment Agency
FAO	Food and Agriculture Organisation
ICZM	Integrated Coastal Zone Management
IPCC	International Panel on Climate Change
MEA	Millennium Ecosystem Assessment
MPA	Marine Protected Area
SAV	Submerged Aquatic Vegetation
UNEP	United Nations Environment Programme
WIO	Western Indian Ocean
WIOMSA	Western Indian Ocean Marine Science Association

Introduction

The intertidal zone provides several important key ecosystem services, and is thus of great value to humans, yet the important benefits are poorly understood and there is a lack of reliable economic estimates (Barbier et al. 2011). As the intertidal zone is a highly dynamic part of the global ecosystem it is prone to natural and human-induced global change (Crossland et al. 2005). Intertidal ecosystems are experiencing an accelerating loss of biodiversity and the potential consequences for ecosystem services and human well-being are still largely unknown (Balmford and Bond 2005; Lotze et al. 2006; Worm et al. 2006; Waycott et al. 2009). The ever increasing human coastal population and the associated pressures are powerful catalysts for direct and indirect changes in the intertidal zone (Shi and Singh 2003; Crossland et al. 2005). Many of these changes are negative such as habitat degradation and biodiversity loss, which are mainly caused by overexploitation of resources, poverty, natural disasters, fisheries, coastal development, erosion and climate change. (IPCC 2001; UNEP 2002; UNEP 2004; Crossland et al. 2005; Halpern et al. 2007).

Severe effects in nature may be expected when foundation species are affected and a community may shift towards another, and the new system often having different structure and function than the previous one (Scheffer et al. 2001; Folke et al. 2004). The intertidal zone is easy accessible and provides for multiple human use, such as intertidal harvesting and harbour activities, which may threaten the intertidal environment. It is clear that we must improve the management of habitats and biodiversity threatened by human activities within the intertidal zone to ensure sustainability. The challenge is that this must be achieved in the face of the pressures from land and sea, including both natural and anthropogenic pressures. For successful management, we must try to understand and determine the driving forces, pressures, status, impacts and responses (DPSIR; EEA 2007) and their interactions as well as synergistic effects at different scales. Further, it is important to monitor how ecosystems respond to, and possibly adapt to, a changing environment when several factors are acting simultaneously. The high human value of the intertidal zone along with multiple threats creates unique management and conservation challenges (Sloan et al. 2007).

Scope of thesis

Problem statement and aim

Most ecosystems located in the intertidal zone in the Western Indian Ocean (WIO) are not formally recognized as important, have unregulated usage and/or lack formal management. The low formal understanding of intertidal values, ecosystem goods and services, utilization and threats creates a situation where the intertidal zone receives very little attention and is not prioritized for research, monitoring and management. The major aim of this thesis was to achieve a better understanding of the poorly investigated intertidal zone in the tropical and subtropical WIO.

Analytical framework

We urgently need to improve our understanding of how to best manage intertidal areas and ecosystem management provides an appropriate framework for this. Ecosystem management is considered a very effective approach to natural resource management (Grumbine 1994; Meffe et al. 2002). It can be defined as "the careful and skilful use of ecological, economic, social, and managerial principles in managing ecosystems to produce, restore, or sustain ecosystem integrity and desired conditions, uses, products, values, and services over the long term" (Overbay 1992), i.e. it has a collaborative approach which considers ecological, socioeconomic and institutional perspectives to identify solutions acceptable to all (Meffe et al. 2002). It recognizes that humans are part of the ecosystem and acknowledges the importance of human needs while at the same time confronting the reality that we depend on nature (Carroll and Meffe 1997; Hale and Adams 2007).

For ecosystem management to be successful it should be based on knowledge developed from monitoring and research on e.g. distribution of organisms, ecological interactions and processes necessary to sustain ecosystem composition, structure, and function (Christensen et al. 1996). So, to effectively manage our resources we need to have and understand scientific data on the status, trends, processes and interactions among ecosystems, as well as values and threats on different spatial and temporal scales (Grumbine 1994; Christensen et al. 1996; Reagan 2006). Improved understanding (through e.g. assessments, feedback and communication, etc.) will lead to more informed decision-making and better social discourse on various issues (Dennison et al. 2007). The dilemma is that there is a lack of research, monitoring and specific management actions for most intertidal ecosystems in the WIO (except mangroves and large flagship species) and the unfortunate general separation of terrestrial and marine environments, which traps the constantly shifting intertidal zone between the two environments (**Paper I**).

To be able to conduct effective management we need to a) know the driving forces for change, b) know the state of and pressure on the resources, c) know the impact, i.e. the consequences for environment and humanity, d) work out the response, i.e. what is being or can be done and are current methods efficient?, e) develop scenarios, e.g. identify desired situation/future (Fig 1), and f) outline what the options for action are. As a necessary step to increase the pool of knowledge needed for increased sustainability of intertidal zones in the WIO the specific objectives in this thesis were to:

(1) Assess habitats, values, threats and current research, monitoring and management of the intertidal area to identify the current situation and future needs through an expert opinion survey (**Paper I**).

(2) Investigate the effects of anthropogenic disturbances such as local harbour activities and the ignored unregulated intertidal invertebrate fishery on seagrass habitats, associated species and biodiversity (**Paper II, III**).

(3) Investigate how intertidal fishery affects local coastal livelihood (**Paper III**).

(4) Identify, evaluate and discuss potential management strategies for intertidal areas (**Paper I**).

(5) Test an environmental monitoring method (remote sensing) to improve the understanding of the distribution of intertidal habitats and the potential of estimating seagrass biomass (**Paper IV**).

This thesis provides information on the intertidal zone and applications for management through a multidisciplinary research approach, and it also provides innovative ways to explore the ecosystem-management toolbox.

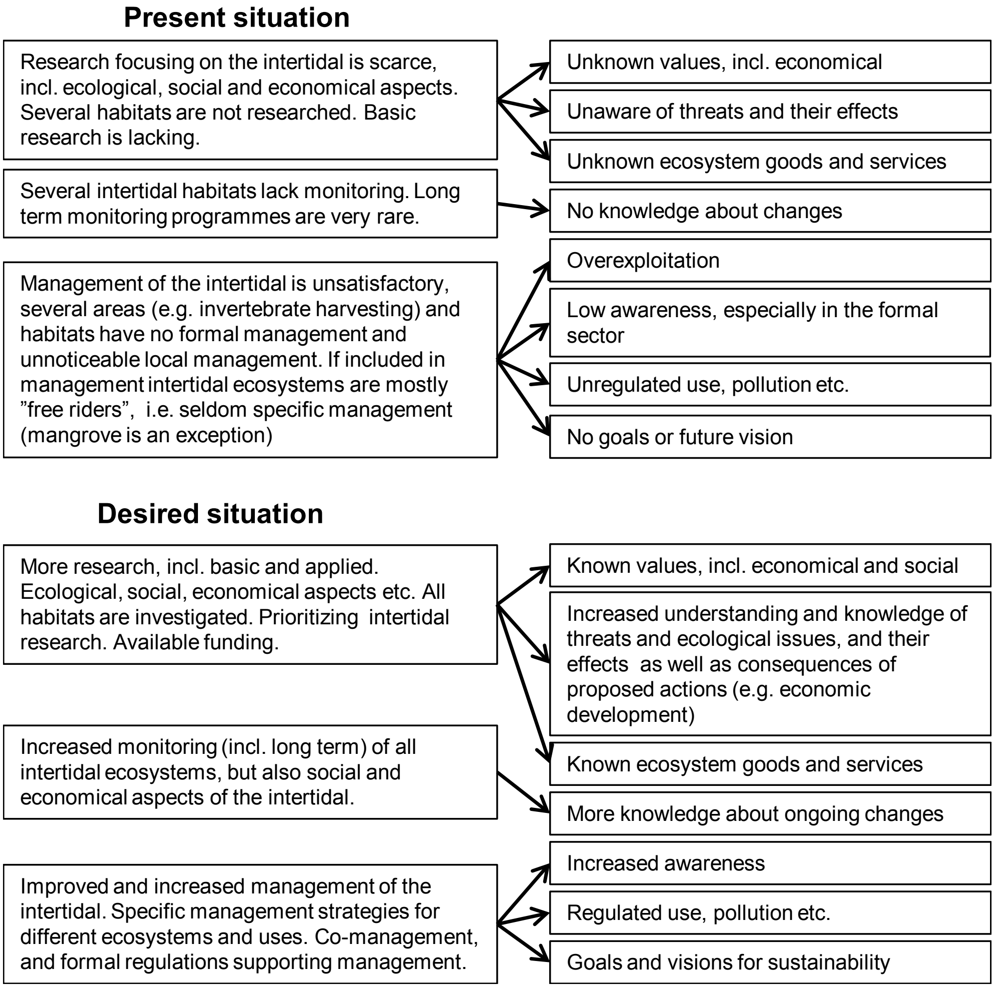

Figure 1. A conceptual model of the present and desired situation for research, monitoring and management of the WIO intertidal zone.

A typical intertidal environment with a sandy beach, mangrove, sand/mudflat, patchy algal bed and seagrass meadows in Zanzibar, Tanzania. Photo: Lina Mtwana Nordlund

A busy beach with hundreds of people swimming in the water in Mombasa, Kenya. Photo: Frida Lanshammar.

Theoretical framework

Drivers of change

Drivers can be both anthropogenic and natural factors that directly or indirectly cause a change in an ecosystem and these driving forces are almost always multiple and interactive (MEA 2005). But the root causes for environmental change are undoubtedly mainly human related activities (Valiela 2006). This change is largely due to the growing population and exploitation pressures as nearly 40% of the people in the world (i.e. > 2.8 billion people) live within 100 kilometres of the coast (MEA 2005). Humans and nature are interlinked, i.e. human activities affect nature which in turn influences human well-being (Berkes and Folke 1998; Chapin et al. 2009). For example, human pressure on intertidal resources comprises several ecosystem services crucial to human well-being.

Habitat loss and fragmentation

Several intertidal habitats are threatened; recently IPCC (2007) estimated a loss of about 30 % of all coastal wetlands globally. For example mangrove forests have decreased with approximately 20-35% since 1980, similar to the rates of both tropical rain forests and coral reefs (Valiela et al. 2001; FAO 2007) and this is mostly due to human alterations such as mariculture, agriculture, urbanization, and forestry uses (Fortes 1988; Marshall 1994; Primavera 1995). Salt marshes have been degraded or lost globally to an approximate extent of 50% (Bromberg-Gedan and Silliman 2009; Bromberg-Gedan et al. 2009). Further, 29% of the known seagrass distribution has been lost (Waycott et al. 2009), mainly due to a multitude of anthropogenic activities such as nutrient enrichment, sediment overloading, accumulation of contaminants, physical disturbance e.g. boat and propeller scars, etc. (Zieman 1976; Sargent et al. 1995; Orth et al. 2006).

Seagrass is one of the important and valuable habitats in the intertidal system as they often hold a higher diversity than the surrounding matrix (Almeida et al. 2008). Seagrasses also provide important ecosystem goods and services for the coastal human population, through fishing, seaweed farming, collecting/harvesting of invertebrates, protection against coastal erosion, cultural and social values (e.g. de la Torre-Castro and Rönnbäck 2004; de la Torre-Castro 2006; Unsworth and Cullen 2010; Gullström et al.

2012a. **Papers II** and **III**). Seagrass ecosystems receive little attention compared to other estuarine and coastal systems (Duarte et al. 2008).

Mangroves, salt marshes, and seagrasses are examples of so called ecosystem engineers, because they are developing the habitat structure and function of the system, and therefore profoundly affect community structure, biodiversity and ecosystem processes (Jones et al.; 1994, Coleman and Williams 2002) and these habitats are known for their ability to stabilize shorelines and protect coastal communities (Gedan et al. 2011). With ecosystem alterations, degradation and habitat loss/fragmentation the organisms using the habitat at a particular site will be affected, displaced or lost resulting in reduced biodiversity.

Biodiversity loss

Biodiversity, defined as the diversity of genes, populations, species, communities and ecosystems, underlies all ecosystem processes. The knowledge on biodiversity is uneven, generally with good knowledge of e.g. large animals and temperate systems but gaps in knowledge of tropical systems, invertebrates, and marine and freshwater biota (MEA 2005).

A majority of species within higher taxa is in decline and humans may have increased species extinction rates over the past few hundred years by as much as three orders of magnitude (MEA 2005). This is a problem since several studies have shown that the function of an ecosystem is supported and improved by a high biodiversity, both in terrestrial and aquatic ecosystems (e.g. Emmerson et al. 2001; Solan et al. 2004; Cardinale et al. 2006). Also, decreased biodiversity most often results in decreased response diversity, i.e. the ability of species that contribute to the same ecosystem function to respond differently to environmental change (Elmqvist et al. 2003). The response diversity is critical to support resilience, the amount of disturbance the system can absorb, as well as to be able to handle future uncertainty (Elmqvist et al. 2003). When humans reduce resilience in a complex adaptive ecosystem, e.g. by taking away a whole trophic level or a whole functional group, a regime shift can occur, a shift from a desired to an undesired state regarding their capacity to generate ecosystem services, i.e. benefits from ecological functions (Folke et al. 2004).

The global marine biodiversity is in a rapid decline due to mostly a synergy of human threats such as overfishing, global warming, species introductions, and pollution. Coastal fisheries have depleted stocks of finfish, crustaceans, and molluscs in all regions of the world (MEA 2005). For example, the majority of the world's fish stocks are overexploited and a "race for fish" has evolved in several places, but in areas where management addresses these problems there is a potential for future sustainability (Hilborn et al. 2003). Invertebrate fisheries are however increasingly exploiting the invertebrate stocks, and the fishing is often conducted with habitat destructive gear (Anderson et al. 2011). The formal knowledge about invertebrate fisheries, especially less established fisheries, is under-developed, i.e. often not assessed, monitored or regulated (Levia and Castilla 2002; MEA 2005; FAO 2009; Anderson et al. 2011). The negative effect of overexploitation and habitat destruction by man on biodiversity causes serious problems for local people, who depend on the organisms in these ecosystems for their livelihood, especially in poorer regions such as the WIO.

Invertebrate harvesting

Invertebrate harvesting (also known as gleaning or collection of e.g. molluscs and echinoderms; Fig 2) in the intertidal zone is a commonly practised activity around the world and especially in tropical and subtropical areas on hard substrates (Hockey and Bosman 1986; Keough et al. 1993; Whippy-Morris 1995; Moreno 2001; Rius et al. 2006) and soft bottoms (de la Torre-Castro and Rönnbäck 2004; Nordlund et al. 2011a; **Papers II** and **III**). However, this fishery is largely unquantified (Unsworth and Cullen 2010), especially its consequences for biodiversity, ecosystem function and local livelihood. Research of invertebrate harvesting on Chilean rocky shores has shown that humans change the intertidal community patterns (Moreno 2001). Addessi (1994) investigated organisms susceptible to collection for food, bait, or aquaria in a rocky intertidal habitat and observed that density of most macro-organisms decreased due to these human activities. Further, the invertebrate fishery might not only affect target species as cascading trophic effects can change community structure and ecological processes (Durán and Castilla 1989; Castilla 1999; Scheffer et al. 2005, Moksnes et al. 2008). Even though invertebrate harvesting is a common practice it receives very little or no research, monitoring and management attention, especially in the WIO and when practiced on soft substrates (Nordlund et al. 2011a; this thesis; **Paper I**).

In the WIO, women are predominantly involved in the invertebrate harvesting, which is commonly conducted on rocky shores, in mangroves and seagrass meadows (**Papers II** and **III**). For example, it is recognized that women in Tanzania have a significant role in fishing outside the formal fishing sector (Jiddawi and Öhman 2002), but this harvesting still lacks formal management.

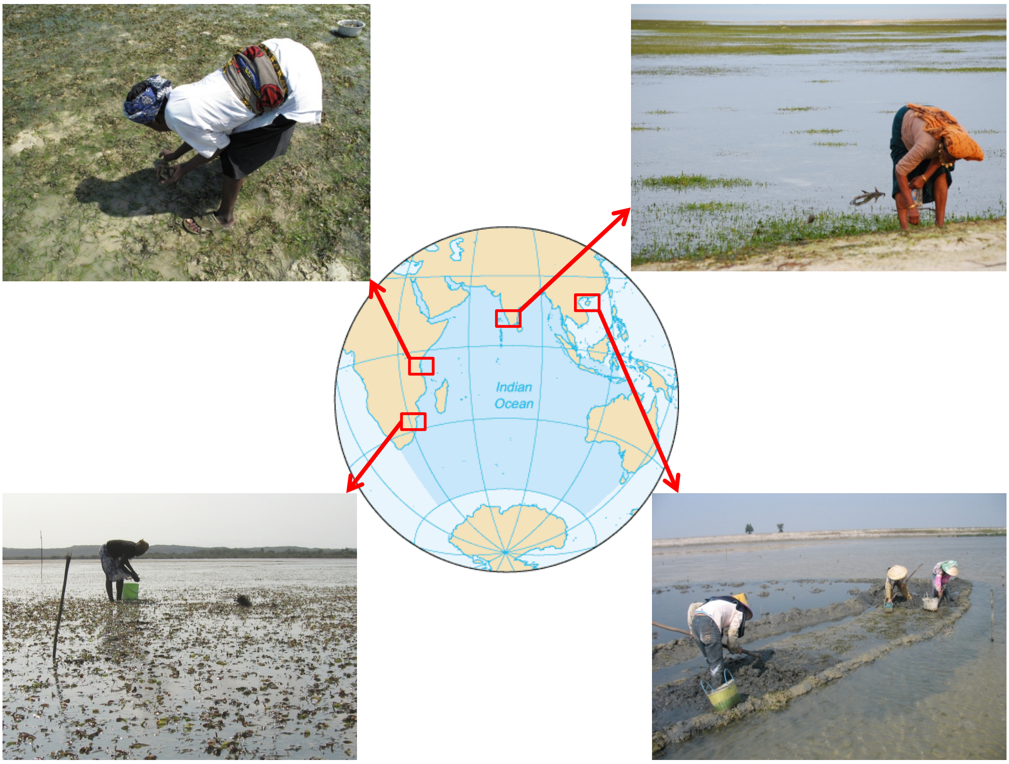

Figure 2. Invertebrate harvesters in the Indian Ocean and South China Sea. Top left: Women harvesting invertebrates in a mixed seagrass bed dominated by *Thalassia hempricii* on Zanzibar, Tanzania. Photo: Lina Mtwana Nordlund. Top right: Invertebrate harvester in a seagrass bed on Bangaram Island, India. Photo: P. Lakshadwee. Bottom left: Invertebrate harvester in a *Thalassodendron ciliatum* seagrass bed at Inhaca Island, Mozambique. Photo: Lina Mtwana Nordlund. Bottom right: Destructive invertebrate harvesting in a *Halophila ovalis* seagrass meadow at Zhulin, Beihai City, Guangxi, China. Photo: Guanglong Qiu. The globe: Wikimedia Commons; http://pam.wikipedia.org/wiki/File:Indianocean.PNG

Implications for sustainable management

In the WIO several conflicts and problems are involved in local to regional conservation issues (Balmford et al. 2001; Masalu 2003). Management of intertidal resources is poorly carried out in the WIO region (**Paper I**). To maintain the diversity and productivity of intertidal resources, improve people's livelihoods, and sustain national economies more effective management is needed, since sustainability requires that the reproductive base is maintained or increased (Francis et al. 2002; Chapin et al. 2009). For successful management there is a need for increased communication between research and management (Lauber et al. 2011). Moreover, to increase the probability of successful management and conservation it is important to understand, address and incorporate stakeholders' socioeconomic needs and concerns (Cinner and David 2011) and understand stakeholders' willingness and ability to conduct alternative livelihoods, e.g. exit fisheries and pursue farming (Daw et al. 2012). In other words social integration is essential and could be done through facilitating and catalyzing local-level adaptation (McClanahan et al. 2009). Furthermore, the division of land and sea is problematic for the intertidal zone as it is located in the land-to-sea continuum (Banks et al. 2005; Sloan et al. 2007). For example, most selection models for marine or terrestrial reserves are not considering the ecological interactions between the land and sea (Stoms et al. 2005), even though integrated land and sea conservation planning is essential for success (Álvarez-Romero et al. 2011).

Habitat and biodiversity loss is a fact (e.g. MEA 2005) and it is important to understand why it occurs, but it is even more important to focus on what we can do with our existing environmental assets. Ecosystem management is a progressive approach to natural resource management focusing on both ecological and human needs in the future by integrating social, environmental and economic perspectives. It is an adaptive approach that considers changing needs and new information. The European Environment Agency (EEA) uses the DPSIR (Driving forces – Pressures – State – Impact – Responses) framework for increased sustainability. DPSIR is a systems analysis view, where social and economic development induces environmental changes which impact e.g. humans and the ecosystem. These impacts might cause people to take action that feeds back on the driving forces, pressures, on the state, or the impact through adaptation or action. Whatever approach or framework is being used to improve sustainability it is clear that we need adequate information for effective management, especially in complex decision-making processes. Without a sound scientific basis, impact assessments for existing and planned activities of good management decisions are hard to make (see e.g. Nobre 2011). Expectantly, the results from this study will be useful in guiding management policies.

Environmental monitoring

Monitoring is a valuable tool as it provides information whether the condition of a resource is stable, changing, improving or declining and where it is happening. This information can be used as e.g. basis for management or feedback to ongoing management. Seagrasses are considered good biological indicators since they respond to both natural and anthropogenic changes and can register changes in environmental variables (Abal and Dennison 1996; Romero et al. 2007).

Remote sensing can be used to create maps and for monitoring purposes among other things. The advantage to use remote sensing (by satellite) is that: (i) it can cover large areas, (ii) it has great accessibility and cover, which makes it cost-effective, (iii) it collects data without physical presence, (iv) satellite imagery provides different spectral possibilities for analysis, and (v) satellites cover inaccessible, remote areas.

Study area

The Western Indian Ocean (WIO) region refers to the African coastal states of Somalia, Kenya, Tanzania, Mozambique and South Africa together with the Indian Ocean island states of Mayotte and Reunion (France), Comoros, Madagascar, Mauritius and Seychelles (Fig 3a; UNEP 2007; UNEP/Nairobi Convention Secretariat and WIOMSA 2009). The region is crossed by the equator, allowing a generally tropical climate, except the subtropical conditions in Southern Africa (Arthuron and Korateng 2006; UNEP/Nairobi Convention Secretariat and WIOMSA 2009). The WIO mainland coast is 13,000 km long from Somalia to South Africa and the island states have a coastline of 6,360 km (UNEP/Nairobi Convention Secretariat and WIOMSA 2009).

An increasing environmental degradation is being observed in several places in the WIO region, and this degradation is likely due to rapid population growth and overpopulation in the coastal zone (<100 km from the coast), widespread poverty, destructive resource exploitation, over-exploitation and poorly planned development of the coastal zone (Jiddawi and Öhman 2002; Shi and Singh 2003; Pauly et al. 2005; Rocliff 2010). The region is well described by Coughanowr et al. (1995).

The case studies in this thesis were conducted in Tanzania (Fig 3b) and Mozambique (Fig 3c). The field work of **paper II** was conducted at Inhaca Island in southern Mozambique, which has a subtropical climate. Fishing is the main subsistence activity and the inhabitants suffer from poverty. Intertidal harvesting by women has no formal regulation. The environment of Inhaca is well described by Kalk (1995). The field work of **paper III** was conducted on north-eastern Unguja Island (main southern island of Zanzibar, Tanzania). Unguja has a tropical climate, is overpopulated, and the main activities are fishing and tourism. Intertidal harvesting by women has no formal regulation. Of the 13 seagrass species known in the WIO region (Bandeira and Björk 2001, Gullström 2002) five species are found in north-eastern Unguja (personal observations).

The field work of **paper IV** was conducted around Chumbe Island, a small island located off south-western Unguja. The area west of Chumbe Island was gazetted a no-take zone in 1994 and the management for the marine protected area (MPA) is provided by Chumbe Island Coral Park Ltd.

The award winning park gained recognition from the UN Secretary General in 2011 (UN Secretary-General 2011) for their innovative private management to protect the Chumbe coral reef. Their management plan is focused on the coral reef. The Chumbe intertidal zone hosts seven seagrass species. Detailed study area descriptions can be found in the enclosed individual papers.

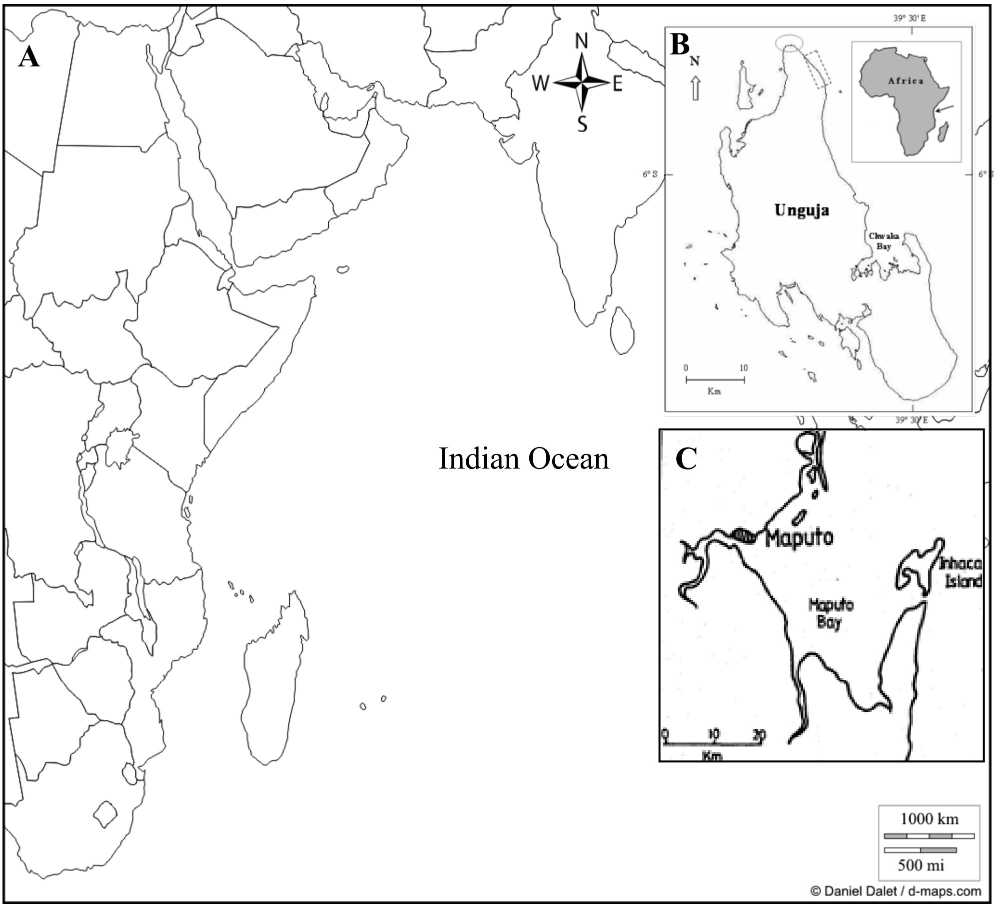

Figure 3 A) Map of the Western Indian Ocean (www.d-maps.com/), B) Map over Zanzibar, Tanzania, and C) Map over Maputo Bay and Inhaca Island, southern Mozambique.

The intertidal zone

The intertidal zone is a part of the coastal zone where land and sea meet, and is located between the extreme high water springs (EHWS) and the extreme low water springs (ELWS; Fig 4). In the WIO, the tidal range is 0.4-6 meters depending on the geographical location of the intertidal zone, with larger ranges more eastward. Depending on the topography of the intertidal zone, the area can become very large, i.e. several kilometres. The tides in the region are predominantly semidiurnal (two high tides and two low tides each day/night cycle). The intertidal environment is constantly changing due to the submersion during high tide and exposure during low tide, creating extreme conditions for several variables, such as temperature, salinity and physical dynamics. The WIO is affected by the southern (generally June-September) and northern (generally November-March) monsoons influencing temperature, rainfall and winds (McClanahan 1988). The tides drive human activities, such as fishing, mangrove cutting and invertebrate harvesting.

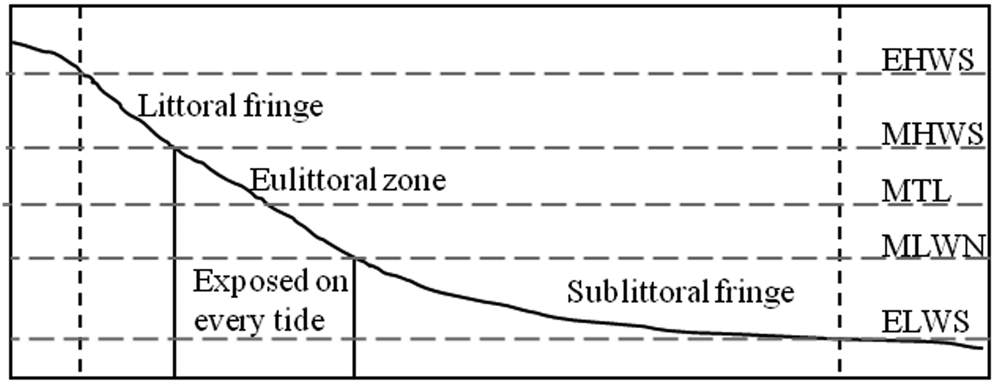

Figure 4. A schematic picture over the intertidal zone, showing the different tidal regimes. EHWS (Extreme high water springs), MHWN (Mean high water neaps), MTL (Mean tide level), MLWN (Mean low water neaps), ELWS (Extreme low water springs). The littoral fringe (between EHWS and MHWS) is only covered by the sea during high spring tides, but a few days a year the sea can reach past this zone to the supralittoral. The sublittoral (between MLWN and ELWS) is only exposed near or during spring low tide. The littoral fringe, the eulittoral zone and the sublittoral fringe together form the littoral zone, i.e. the intertidal. Picture adapted from Richmond (2002).

Intertidal habitats

There are many different types of habitats associated with the intertidal zone in the WIO. More landward (mostly dry) there are habitats such as salt marshes, and moving seaward (more and more often covered by sea) there are sandy beaches, rocky shores, mussel beds, mangroves, estuaries, mud flats, seagrasses, lagoons and algal beds. The habitats are interlinked and interrelated, and effects one habitat may therefore also affect other habitats. The ever changing environment and a combination of factors affecting the environment create a very diverse area (Holland and Elmore 2008).

Salt marshes are usually found on a flat area landward from mangroves, and are dominated by grassy salt-tolerant plants with periodic salt water inundation. There is barely any research on salt marshes in the

WIO, while they are well researched in other parts of the world (Townend et al. 2011). Sandy beaches are common in the region and attract tourists and the local population alike (Barbier et al. 2011). Bays and estuaries with intertidal sand and mudflats are found in most parts of the region, larger in the mainland states and smaller in the island states.

Rocky shores are common in the WIO and are mostly present above the mid-eulittoral, and they often have a clear zonation of different epifauna, e.g. mussel beds, barnacles and limpets (Thompson et al. 2002). Mangroves are found in the mid to upper intertidal zone, and there are nine common species in the WIO (Richmond 2002). Mangroves are well known for their rich biodiversity and that they play a key ecological role in the coastal environment (Spalding et al. 1997). Thirteen seagrass species are known in the WIO region (Bandeira and Björk 2001, Gullström et al. 2002). They are found in the lower intertidal and subtidal. They also play key ecological roles in the coastal environment, e.g. as nurseries, as seabed stabilisers and for oxygenation of sediments (Green and Short 2003). Lagoons are common in the region and often separate beaches and cliffs from the coral reef (Richmond et al. 2002). Algal beds are common and there is a fairly clear zonation of these organisms in the intertidal zone (Oliveira et al. 2005).

There are relatively comprehensive inventories of species of intertidal gastropods and echinoderms, mangroves, seagrasses, marine algae, and birds in the region (Richmond 2002; Muthiga and Kawaka 2010). There is also some research within the coastal geomorphology field in the region (see e.g. Kairu and Nyandwi 2000).

Methods

A multi-disciplinary approach was used, including interview forms, workshop discussions, ecological/biological field sampling, interviews, observations and remote sensing. In the following section a summary of the specific methods of each objective is given. Detailed descriptions are found in the enclosed individual papers.

To examine objective 1, i.e. to increase the understanding the intertidal zone, expert opinions were gathered through interview forms and workshop discussions. This was done at the 7th Western Indian Ocean Marine Science Association (WIOMSA) Scientific Symposium (24-29 October 2011) in Mombasa, Kenya, which provided the opportunity to meet a large group of scientists and practitioners, many with significant experience from the WIO region. The interview form with opened and closed questions was distributed carefully to participants that met the set requirements. Part I of the interview form with opened questions was used to cover objective 1 (i.e. habitats; values; current and potential threats; current status of research, monitoring, and management; and future needs of the intertidal zone). The workshop was open to all interested symposium participants and the first part of the workshop with open floor discussions was also used to cover objective 1 (**Paper I**).

Objective 2, i.e. to investigate anthropogenic disturbances on biodiversity, was conducted by measuring density, biomass, species richness and community structure of invertebrates, as well as seagrass characteristics, and compare among three different areas of human exploitation (a protected area, a harbour area, and an area exploited by invertebrate fishers) in tropical (Tanzania) and subtropical (Mozambique) environments of WIO. Laboratory work, drying, measuring and weighing seagrass and invertebrates, was conducted according to or adapted from Short and Coles (2001). Balanced analysis of variance (ANOVA) with nested design, one-way ANOVA, post-hoc Tukey test, and unpaired two-tailed or one-tailed 2-Sample *t*-tests were used to compare the different sites (Mann-Whitney *U*-test was used when data were non-normally distributed) using Minitab 15 Statistical Software. Data were transformed prior to analyses when needed. Multivariate statistical techniques were used to detect patterns in community composition of seagrass assemblages using

Primer version 5.2.4 and 6 (Clarke and Gorley 2001). One-way analysis of similarities (ANOSIM) and the similarity of percentages (SIMPER) were used to detect more details (**Papers II** and **III**).

Objective 3, i.e. social-ecological aspects of invertebrate harvesting and biodiversity changes, and how local livelihood is affected, was investigated through structured interviews with invertebrate harvesters using mostly open-ended questions. The interviews were evaluated through meaning condensation and meaning interpretation (Kvale 1996). Observations were done both on land and in water to increase the understanding of species harvested, harvesting methods, species abundance, habitat and invertebrate characteristics (**Paper III**).

Objective 4, i.e. to identify, evaluate and discuss potential management strategies for the intertidal in the WIO, used part II of the interview form and workshop discussions with intertidal researchers and managers in the WIO at the 7th WIOMSA Scientific Symposium. Part II of the interview form had mostly closed questions with open follow-up questions to identify among suggested management strategies which are considered most important, feasible and confidently conducted by using a scoring system. The second part of the workshop was conducted in smaller groups to discuss the management suggestions and their implications, use and potential outcome. The data was explored with R and multivariate analyses, and presented using Primer version 6 (Clarke and Gorley 2001) (**Paper I**).

Objective 5, i.e. to test a potential environmental monitoring method, was carried out by testing the utility of satellite imagery to map the variables in a typical nearshore environment (with a diverse mix of inter- and sub-tidal habitat types), with 7 species of seagrass at varying depths, distributed in patches of different sizes, i.e. resembling a "real-world" situation and not just a good testing ground. Ground-thruthing and seagrass biomass estimations were done in random quadrates covering all habitats and all seagrass densities, respectively, while snorkelling with GPS. For the biomass estimation, we used a visual scale developed according to Mumby et al. (1997). We used IKONOS imagery, which provides colour and infrared data at high resolution (4 x 4 meters). Numerous methodologies are available and we used different methods depending on stage image processing (Akaike 1974; Lyzenga 1978; Efron and Tibshirani 1993; Mumby et al. 1998; Stumpf et al. 2003; Hedley et al. 2005). We also compared the utility of the results with a field based study to distinguish the pros and cons (**Paper IV**).

Synthesis of results │Meeting the objectives

Objective 1: Assessment of the intertidal

Paper I frames this thesis by assessing the current knowledge and understanding of the intertidal in the WIO. The aim was to conduct a scientific literature review, but with the present scarcity of information about the intertidal zone in the WIO an expert opinion study was conducted. The experts concurred that there is a clear lack of research in the WIO concerning most ecosystems/habitats commonly associated with the intertidal area, as well as in many geographical areas.

The experts identified a broad variety of important habitats in the intertidal zone, such as mangroves, seagrasses, rocky shores, mudflats and sandy beaches. They also stated that intertidal zones are highly valuable for several reasons, such as beaches, seagrasses and mangroves improving water quality and protecting the shoreline as well as providing edible invertebrates and fishes. The zone is used by basically everyone, due to the varied "landscape" and "high value" for humans. Furthermore, there seems to be an overwhelming amount of threats to the intertidal zone at all scales (according to the experts), such as pollution, over harvesting, habitat destruction, climate change, overfishing, erosion and costal development and construction. Monitoring projects are scarce and in many cases absent, and management attention is very low in most countries, probably due to the fact that values of the intertidal are often unknown because the low amount available data and research. The majority of the experts (86%) said that there was not enough knowledge about the intertidal area in general except for a few geographical areas and ecosystems. The experts listed a wide variety of aspects that needs to be managed or controlled in the intertidal area, such as over-harvesting, fisheries, development, construction, pollution and erosion.

Objective 2: Anthropogenic disturbances on biodiversity

Paper II (performed at Inhaca Island, Mozambique) showed that the protected site, without direct anthropogenic disturbance, by far comprised of the highest invertebrate density, biomass and species richness compared to the areas with invertebrate harvesting and harbour activity (Fig 5). The *Thalassodendron ciliatum* dominated seagrass habitats showed no significant differences in above-ground seagrass biomass among sites, but slightly taller shoots in the harbour compared to the other two sites. Multivariate statistics showed a clear separation between the protected and exploited sites due to e.g. animal density, biomass and species richness between the protected and exploited sites.

The analysis of the inventory data in **paper III** (performed at Zanzibar, Tanzania) showed that the unexploited remote site had higher invertebrate density, biomass and species richness/diversity than the site exploited by invertebrate harvesters (Fig 5). There were hardly any differences in seagrass characteristics between the localities studied. Multivariate statistics revealed a weak difference for animal density and biomass among localities. **Papers II** and **III** indicate that human related activities may have large influences on the faunal composition of seagrass meadows and stresses the importance of marine protection in preserving high biodiversity.

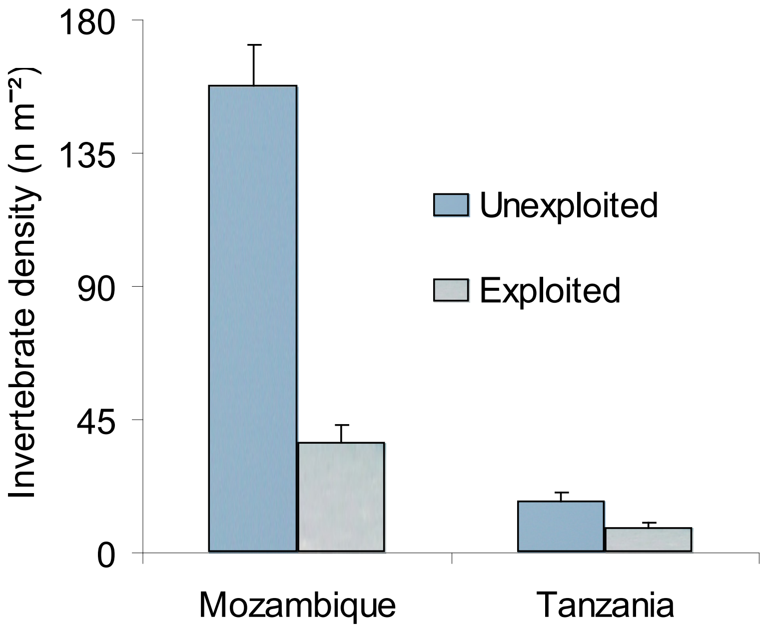

Figure 5. Invertebrate densities in unexploited and exploited (invertebrate harvested) areas (+SE). In Mozambique (Inhaca Island) the unexploited area was protected. The Tanzanian sites (in Zanzibar) investigated are known to be species poor, and the remote unexploited site was located far from human settlement.

Objective 3: Investigate how an invertebrate fishery affects local coastal livelihood

In **paper III** in-depth interviews and observations revealed that intertidal invertebrate harvesting has a strong gender aspect and a long tradition with almost exclusively women harvesting animals. There is an informal institution of older relatives teaching the young how to harvest, what to harvest and to be careful about the environment. This generational information is probably important for the preservation of the intertidal area. Invertebrate collection in Nungwi, Zanzibar is above all a subsistence activity, for securing food but relatively often also for commercial use, since some sell parts of their catch (78% of interviewees).

Harvesting occurs during low spring tide and mostly in seagrass habitats (94% of the interviewees), preferably in large seagrass patches with high to medium shoot density and seagrass cover. All respondents had experienced a decline in seagrass distribution during the last decade, >20% even considering it a large decline. The general opinion among the harvesters was that the species abundance had decreased (replied by 94%), but interesting is that they reported a noticeable decline only during the last decade, suggesting that it has been a more sustainable activity until recently. The current mean catch weight was 1.9 kg/collection day/person (and ca 3 kg and 5 kg 5-10 and 30 years ago, respectively). At present the harvesting women earn ca 63% and 38% of what they would have done if catches were of the same sizes as 5-10 and 30 years ago, respectively.

The number of harvesters has been limited due to small village populations, but during the last 10-15 years the population has increased, tourism has grown, and immigration of people has increased, which has resulted in e.g. more coastal construction, and increased stress on the intertidal area. The main reasons for the decline in seagrasses and invertebrates according to the interviewees are thought to be more harvesters, people being careless about the intertidal area and habitat destruction (by e.g. engine scars, strong winds, and digging). The threat of carelessness on the seagrass ecosystem seems to be recognized among the harvesters, and one of the reasons mentioned for increased carelessness was the higher pressure on local people's livelihoods, which in turn creates a higher pressure on the seagrass ecosystem. **Papers II** and **III** show that invertebrate harvesters can influence faunal compositions in seagrass meadows, which clearly results in negative impacts on local people's economy and livelihood.

Objective 4: Identify, evaluate and discuss potential management strategies
Paper I identifies the level of support for confidence, feasibility and importance for each of the 13 management strategies suggested in the interview form. The level of support for the strategies (in order of highest importance received from the experts) was: 1) Developing integrated coastal zone management plans involving local people. 2) Conduct research on important species and their relation to intertidal ecosystems. 3) Awareness campaigns and education programs. 4) Temporal and/or spatial closures. 5) Establish no-take zones in highly degraded areas together with the community. 6) Habitat maps and remote sensing. 7) Establish size limits for the organisms harvested/fished. 8) Laws against trade of key species and education for tourists. 9) Informal institutions and traditional practices. 10) Integrated mariculture. 11) Strengthening and encouraging the use of traditional and local ecological knowledge. 12) By-laws. 13) Small enclosures to boost larval production.

The scoring for confidence and feasibility provided a slightly different picture, even though the top six are similar with some changes in the succession. Some scores that leap out are e.g. small enclosures and species size limits that received a very low confidence and feasibility compared to importance. Slightly less conspicuous is the low feasibility and confidence compared to importance for integrated mariculture, community no-take zones, and temporal and spatial closures. Research on species ecosystem relationships, and habitat maps and remote sensing were the only management strategies that got a higher confidence score than importance.

This scoring highlights which management strategies that could be tested more thoroughly and repeatedly in the WIO region as a mean to increase sustainability in the intertidal zone.

During the small-group workshop discussions the experts discussed seven of the suggested management strategies (including the addition of formal institutions) and their usefulness, applicability, potential outcomes and further suggestions. The experts stated that formal institutions can lead to better coordinated management, but should be careful with top down decisions. Research is needed to be able to establish size limits (i.e. size for fecundity) and enforcement as well as information to the users are necessary for it to work. No-take zones (NTZ) in degraded areas were thought to be a good idea, but pressure cannot just be shifted elsewhere and site-specific research is needed. By-laws, i.e. location-specific laws, could potentially create more acceptability/legitimacy to rules on a local scale. It is important to develop and implement by-laws with the community, and it could work as a trial before national laws are set according to the workshop discussions.

Integrated coastal zone management (ICZM) plans involving local people were viewed as useful since it would look at all aspects of the coastal zone. Possible outcomes were said to be a better understanding of the zone and a tool for developing alternative livelihood options. Temporal and/or spatial closures were thought to be necessary, but research is needed to position the closures correctly. They would be favourable for the environment, and it is crucial to provide the community with clear information on the reasons behind the closure and there must be enforcement. Habitat maps and remote sensing were said to be important since you must understand your resources, and that it is not a solution but a tool for monitoring and of good assistance in management. **Paper IV** shows that habitat maps and remote sensing are possible to use in the intertidal zone and a cost-effective tool.

Objective 5: Test a potential environmental monitoring method

In the WIO region knowledge of the dynamics of seagrass meadows is limited. As a basis for monitoring efforts, establishing baselines of the distribution, species composition, and biomass of seagrasses is essential. Habitat maps and remote sensing received the sixth highest importance score with high confidence and feasibility scores in **paper I**. In **paper IV** we produced a habitat distribution map of a complex nearshore area with several seagrass species. The map was used to estimate the distribution of seagrass meadows, which was accurately mapped (user accuracy 93.5%), despite some confusion in areas with both seagrass patches and coral bommies of similar size. Seagrass biomass was also accurately estimated (r^2=0.83), except in areas dominated by the seagrass *Thalassodendron ciliatum* (r^2=0.57). The heavy stem of *T. ciliatum* changes the relationship between light interception and biomass from that of the other seagrass species in the area. Different seagrass species could not be separated in the imagery analysis.

Satellite imagery is the only feasible method for mapping seagrasses in large areas, and the results obtained in this study are encouraging. Better results can be expected from newer satellite images with higher spatial resolution, and particularly from hyperspectral images, which has shown potential to distinguish seagrass species. A large-scale seagrass monitoring program in the WIO region can benefit from the methods and results of this study. Follow up studies will also be able to identify differences in seagrass distribution and biomass as well as being beneficial in order to improve management of seagrass meadows.

Illustration of the robust seagrass *Thalassodendron ciliatum* by Lina Mtwana Nordlund.

Discussion

Intertidal values and threats

Intertidal ecosystems support high biodiversity of for example fishes and invertebrates that use these habitats for foraging, protection against predators and as nursery grounds. In addition, they provide many other ecological goods and services, e.g. shoreline protection, recreational areas and harvesting grounds (**Paper I**). The coasts in the WIO countries are becoming an increasingly attractive destination for global tourism, especially the small island developing states (SIDS), where tourism, and its related services, is a main contributor to national economies (Rogerson 2007). Healthy ecosystems are crucial to be able to sustain the people and continue to attract tourists as they are a major source of income.

The intertidal areas are heavily used and host, for example,. harbours, big and small. Nearshore fishing and invertebrate harvesting are common activities in the WIO. The results of this thesis show that invertebrate harvesting and harbour activities negatively affect abundance, biomass, and community composition of invertebrates in seagrass meadows (**Papers II** and **III**). Invertebrate harvesters target certain functional groups, (e.g. filter feeders and macrograzers) which can disturb the balance between organisms or induce changes in the system, and removal of large-sized invertebrates can e.g. lead to reduced fecundity (Branch 1975; Moreno 2001). Following from this, specific functions of the ecosystem may be directly lost or at least reduced. So, the harvesting activity does not only reduce the diversity of species and functional groups, but can also create habitat destruction and/or an ecosystem shift through e.g. trophic cascades. These potential shifts can be maintained by positive feedback, with new and different community structure, ecosystem function and services as a result (Eklöf 2008). Reversion to the original ecosystem may be difficult or impossible to occur naturally, and may require active intervention by man (e.g. Erlandsson et al. 2011).

For the local people living directly from the intertidal biological resources in the poor coastal regions of WIO this has obvious and crucial implications. If the resources (e.g. organisms caught for subsistence and livelihood in e.g. seagrass or mangrove habitats) in the intertidal zone decrease dramatically, or even disappear, an important food and income source will be seriously threatened (**Paper III**).

There is a high possibility that ecosystems located adjacent to disturbed intertidal ecosystems (e.g. seagrass meadows disturbed by invertebrate harvesting), such as coral reefs, will also be affected (Gullström et al. 2008, 2012b). These effects could be e.g. decreasing quantities of migrating invertebrates as well as less available food for reef-associated animals entering the seagrass ecosystem to forage (Unsworth and Cullen 2010). The intertidal also connects the terrestrial and marine ecosystems and with degraded intertidal systems the connectivity between land and sea will be negatively affected.

The major threats and reasons for intertidal ecosystem alteration are of anthropogenic origin. For example, seagrasses are under progressive decline due to anthropogenic activities (Waycott et al. 2009), but additional threats are the ones related to climate change which are certainly very complex and difficult to understand. There might be impacts related to rising sea levels, changing tidal regimes, UV radiation damage, sediment hypoxia and anoxia, increases in sea temperatures and increased storm and flooding events (Björk et al. 2008). To face potential future threats of climate change to seagrass meadows and other intertidal habitats in the WIO, we need to ensure high water quality, favourable water movement, good sediment conditions, genetic variability and connectivity (Björk et al. 2008). This requires pro-active and effective management efforts at local, national and regional institutional levels.

The lack of research, monitoring and management

Paper I revealed that research, monitoring and management strategies in the intertidal zone of the WIO are clearly lacking for most ecosystems, habitats and organisms.

The major challenge for humans is to recognize and manage the consequences of adverse impacts from both natural and human-induced changes to intertidal ecosystems. The clear lack of research, monitoring and management for most intertidal ecosystems (with exceptions of mangroves and some animals) is likely due to the low formal understanding of the importance of the area. Several of the intertidal systems have unregulated use and the ever shifting boundaries create challenges in terms of responsibilities and decision making, etc. There is no doubt that management is needed to achieve sustainability, and for that research and monitoring are needed.

The lack of research (even basic research) in several habitats of the intertidal zone creates a problem. This is because management actions are often based on data gained from research in order to be able to efficiently target the threats, problems, difficulties, and manage and protect the "right things/areas". Another point is that management and science need to be communicated, because otherwise the "point is lost".

As a measure to improve management of habitats and biodiversity, an earlier study by Nordlund et al. (2011a) gathered information about invertebrate harvesting, highlighted the need to investigate management approaches and suggested several possible management actions that could be tested for increased sustainability of invertebrate harvesting in Zanzibar and elsewhere in the region. That paper was also the inspiration to **paper I**.

Environmental monitoring, as well as related applied research, is important as it provides information needed to design, outline, improve and adapt management plans. Without monitoring we are unaware of whether our resources are stable, changing, improving or declining and where the changes are taking place. Further, social and economic drivers and responses must also be monitored and followed up to be able to measure if goals are being met.

Monitoring is expensive and it is impossible to attend to every detail, but one could for example use habitat-forming species and/or bioindicators to assess health. There are several potential bioindicators available in the intertidal, e.g. bivalves and amphipods (Thomas 1993; Boening 1999) as well as seagrasses which are also called the "*coastal canaries*" due to their sensitivity to water quality (Dennison 2009).

Research with remote sensing of seagrass (or submerged aquatic vegetation; SAV) distribution has been conducted around the globe and also in the WIO. A study from Chwaka Bay in Zanzibar (Tanzania) showed a general pattern that the deeper, outer parts of the bay revealed fewer changes in seagrass-dominated SAV compared to the nearshore environment (Gullström et al. 2006). It is an interesting observation, as it shows that SAV in the intertidal might be more dynamic and/or maybe more affected by anthropogenic disturbance than the deeper parts of the bay. The study by Gullström et al. (2006) concludes that repeated mapping with satellite remote sensing is a suitable tool for monitoring changes in SAV distribution in shallow tropical environments.

Habitat distribution is a very important measurement, but since seagrass patches are highly dynamic (they move, become denser, less dense, arise or disappear naturally), in **paper IV** we intended to test if it is possible to estimate seagrass biomass despite strong spatiotemporal dynamics. The distribution of seagrass can remain the same but be more or less dense, or the meadow can have an increased distribution but with severely reduced plant biomass. There are a few seagrass biomass estimation studies done in other parts of the world, but those were carried out on large homogeneous seagrass meadows in very clear waters (Mumby et al. 1997; Robbins 1997). In the WIO region, seagrass areas are often characterized by small and patchy seagrass meadows with a mix of dominant species and less favorable water clarity. Seagrasses as well as other habitats in the intertidal are valuable to humans and it is therefore important to monitor changes in the distribution but also biomass.

Generally management of coastal systems has been and is inadequate to maximize the supply of ecosystem services, but management, policy reforms and up-scaling of small successes can however reverse some of the negative trends, such as habitat degradation (MEA 2005). This means that there is hope and we should now put the focus on available resources and try to do our best to manage those areas. For example, since the first MPAs were established in East Africa in the 1960s and 1970s, 8.1% of the continental shelf in Tanzania had been designated to become MPAs in 2007 (Wells et al. 2007). This does not yet fulfil the 1992 Convention on Biological Diversity, but there is a willingness to try to meet these goals. However, there are many constraints for successful MPAs and other conservation and management initiatives, e.g. excluding people is difficult, management needs capacity building, research, monitoring, and management, and enforcement is costly.

Paper I has identified several potential management strategies and these have been ranked by experts to tease out which were viewed as more important and potentially more successful than other strategies for the WIO. The strategies that received the highest importance were ICZM with local people, species ecosystem relations, awareness and education, temporal and/or spatial closures, community no-take zones in degraded areas, and habitat maps and remote sensing. It would be a good idea to test these strategies further and more systematically, and follow up the results and effects of them.

Managing the intertidal zone?

As outlined in the scope of the thesis; to be able to conduct effective management we need to: a) know the driving forces for change, b) know the state of and pressure on the resources, c) know the consequences for the environment and humanity, d) work out the response, i.e. what is being or can be done and are current methods efficient?, e) develop scenarios, e.g. identify the desired situation/future (Fig 1), f) outline what the options for action are. The situation for the intertidal zone in the WIO is that the low formal awareness and understanding of driving forces, pressures, etc. provides the intertidal zone with low priority (except for mangroves, that is also the most well researched habitat in the intertidal area).

The intertidal zone is heavily used by people, but for sustainability the zone must be managed. However, people must be included in management, especially because it is so valuable to people (e.g. via recreation, coastal protection, and fishing grounds).

I realized in my job as a conservation and education manager for Chumbe Island Coral Park, a no-take MPA with terrestrial and marine components, that there is a low amount of available information about the intertidal ecosystems, as well as a lack of available management strategies, especially in the WIO. So, the reason behind my suggestion that the intertidal zone could potentially be used/operated as one organizational unit in **paper I** is because in the WIO the intertidal is an area with little formal understanding and knowledge. Furthermore, as a manager (or researcher) you might not be aware of many of the values of the intertidal. It is not traditionally managed, and it is an area of change with moving boundaries, and therefore it might receive low priority. In many existing management plans there are already modules, plans, handbooks, etc., for many important sectors (e.g. fisheries) and habitats (e.g. coral reefs and forests), but seldom for the intertidal zone. This is one reason why an organizational unit for intertidal could be advantageous, as it could function as a module that could be added to a management plan. Further reasons for an intertidal organizational unit are that management is traditionally divided into terrestrial and marine environments and they are often not considered together when planning for management and conservation. Moreover, research, monitoring and management are expensive and developing specific strategies for each and every ecosystem in the intertidal is too expensive and time-consuming. Though, the ecosystems within the intertidal often face similar threats, e.g. overexploitation in different forms (e.g. of sand, mangroves, and invertebrates) or pollution, and could therefore benefit from being included in one intertidal unit. They would then at least receive a bit more attention than just being "free riders", and unknown values would be included. The suggested management strategies in **paper I** can in several cases be applied to all systems within the intertidal zone, but for different reasons. One realistic first step to create an organisational unit for the intertidal is to make sub-units with intertidal focus within existing terrestrial and ocean departments resulting in an overlap between land and sea which is forcing the units to communicate.

Organizational unit or not, what is important is that we increase the understanding of threats and values of the intertidal zone and allocate efforts towards research, monitoring and management. Hopefully, the results from this thesis can help identifying and prioritizing intertidal ecosystems in urgent need of research, monitoring and management.

Key findings

1) The intertidal zone is the realm between land and sea, and therefore also exposed to both land- and ocean-based threats. There are many values of the diverse intertidal and it is utilized by humans in several ways, e.g. in swimming, fishing and tourism. There is a clear lack of research, monitoring and management for most intertidal ecosystems in the WIO. Management is clearly needed to achieve sustainability.

2) The heavily populated coastal zone applies pressure on intertidal resources through e.g. harbour activities and the commonly occurring invertebrate harvesting, which both have a negative effect on biodiversity.

3) Invertebrate harvesters target many species (270 different species were identified as targets in northern Zanzibar). It is an important subsistence activity for many women in the WIO as there is widespread poverty and not many other options for obtaining protein. The women recognized that there has been a decrease in invertebrate density and seagrass cover over the last decade, and the decrease clearly results in negative impacts on local people's economy and livelihood.

4) There are several management strategies that should be tested in the WIO, especially Developing integrated coastal zone management plans involving local people; Conduct research on important species and their relation to intertidal ecosystems; Awareness campaigns; Temporal and/or spatial closures; Establish no-take zones in highly degraded areas together with the community. Some strategies received a high diversity of support, i.e. from none to very high, but most provide a high level of support but not the highest. A further question is: Could the intertidal work as one organizational unit?

5) It is possible to map a challenging diverse "real world" intertidal environment and estimate seagrass biomass with reasonable accuracy. Remote sensing is the only feasible method to produce extensive maps and accurately quantify change in habitats and seagrass biomass over time on a large scale.

Future research

Potential future research could aim to build natural and social resilience in heavily utilized intertidal areas by testing several management strategies. There is a need to build awareness and create a will to improve the situation, and prepare for the future when the population increases and climatic changes may alter or disturb ecosystems. Therefore I suggest, based on the outcome from **paper I,** to test Integrated Coastal Zone Management (ICZM) by planning with stakeholders and local communities, to produce a vision along with awareness campaigns to increase the understanding of ecosystem degradation. Further, this kind of research could increase the understanding of how to detect changes, and how to deal with changes and over-exploitation.

The DLIST project has successfully implemented a model called Local Economic Development (Shalli et al. 2011), which can be adapted in this context (Fig 6). The outcome could potentially be a critical evaluation of ICZM involving people, identifying problems on the community level, visions and their understanding of what can be conducted, and how to prepare for ecosystem degradation. It can also provide guidelines for how researchers and managers can work with this strategy and how it can be used to mitigate the challenges of ecosystem degradation and climate change.

The research on awareness campaigns could potentially inform researchers and managers about the available knowledge, what knowledge can be gained from the community and how they feel and think about the environment and natural resources. The outcome could potentially be an evaluation of innovative ways to communicate as well as evaluating peer to peer education to spread environmental knowledge and potential behavioural change (see e.g. Nordlund et al. 2011b).

A further suggestion is to conduct ecological research on important species and their roles within intertidal ecosystems as a mean to understand where to focus on management and where increased resilience is needed. The potential outcome of such research would be to fill the urgent gap of baseline data, information how to gain baseline data from communities, such as this to be able to plan for future management.

Photo opposite page: Zanzibari students engaging in intertidal research, here they are fascinated by a seagrass clearing by *Echinometra mathaei* sea urchins. Photo: Lina Mtwana Nordlund

Additionally, it will be important to test the establishment of temporal and spatial closures as well as to create no-take zones in highly degraded areas in close association with the local community. As a means to promote natural resilience and make sure there are refuges that have a chance to adapt to environmental change and can later potentially work as a source for other areas. The outcome of this could potentially provide suggestions on how to conduct closures and if it can be a way to increase awareness about the importance of sustainable use and as a measure to prepare for climatic changes.

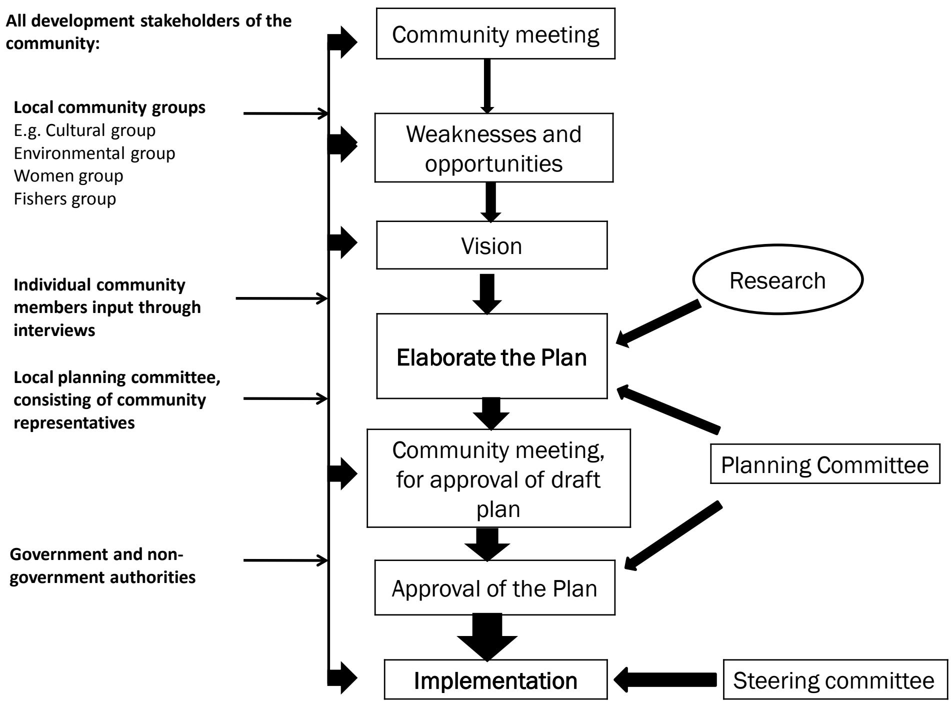

Figure 6. Local working plan, adapted from Shalli et al. (2011).

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To conclude

a couple of photos from the

Western Indian Ocean region

Photo 1) An exposed sandflat with palm trees swaying in the wind. Photo Lina Mtwana Nordlund.

Photo 2) A patchy seagrass meadow and women on their way out to harvest invertebrates. Photo Lina Mtwana Nordlund.

Photo 3) Women looking at their catch. Photo Lina Mtwana Nordlund.

Photo 4) Costal construction in the intertidal zone and seawall trying to stop the water from eroding away the hotel property. Photo Lina Mtwana Nordlund.

Photo 5) A seagrass meadow and fishers going out with their boats. Photo Lina Mtwana Nordlund.

Lina Mtwana Nordlund

People and the intertidal

Human induced changes, biodiversity loss, livelihood implications and management in the Western Indian Ocean

This PhD dissertation deals with the intertidal zone in the Western Indian Ocean. It describes the status and general threats with a focus on invertebrate harvesting and harbour activities. Further, it deals with consequences for local livelihoods and describes current research, monitoring and management, as well as discusses potential strategies for improved management.

The author

Lina has been working with natural resource management and environmental research in the Western Indian Ocean region since 2005 and she started her PhD in December 2009. She is using a multi-disciplinary approach in her work and uses techniques such as ecological/biological field sampling, field experiments, field observations, remote sensing, interviews, questionnaires and workshop discussions.

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