Integrating Insights from Social-Ecological Interactions into Sustainable Land Use Change Scenarios for Zanzibar

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THESIS ABSTRACT

Small islands in the Western Indian Ocean face complex social-ecological challenges arising from climate change and anthropogenic pressures. These greatly impact the way in which people interact with their environment to meet their basic needs. Consequently, there is a need to explore social-ecological relationships and their dynamics in response to change. This project used a water-energy-food nexus lens to explore these social-ecological relationships in the two largest islands that comprise the Zanzibar archipelago, Unguja and Pemba. These insights were integrated into alternative scenario narratives to produce contextually relevant and robust models for future resource security. Key findings across the project showed land use and resource competition, deforestation, climate change and insufficient resource infrastructure caused resource insecurity. Areas further inland was found to experience a differentiated set of water-energy-food challenges currently not well represented in wider research in small islands. Spatial characteristics such as remoteness, intensity of land use and amount of natural resource capital impact the scale and strength of resource insecurity. Scenarios modelling indicated that deforestation, saltwater incursion, and a reduction in permanent water bodies was expected by the year 2030 in a *Business as Usual Scenario*. Three alternative scenario narratives were developed by participants, these included *Adaptation, Ecosystem Management* and *Settlement Planning*. However, the effectiveness of actions under the scenario options were predicted to differ across the islands, indicating the importance of understanding the suitability of national policies across scales. Synergies across the scenario narratives also emerged, these included integrated approaches for managing environmental change, community participation in decision-making, effective protection of forests, cultural sensitivity to settlement planning, and poverty alleviation. These synergies could be used to plan strategic action towards effectively strengthening water-energy-food security in Zanzibar.

Dedicated to my father

Paul Newman

AUTHORS DECLARATION

I declare that this thesis is a presentation of original work, and I am the sole author. This work has not previously been presented for an award at this, or any other University. All sources are acknowledged as references.

Four of the thesis chapters have been published in peer review journals. I can confirm that I was responsible for developing the theoretical framing, designing the methodology, carrying out all data collection and analysis, developing arguments, and writing and revising the manuscripts throughout the review process. As supervisors and coauthors, Claudia Capitani, Jessica Thorn, Colin Courtney-Mustaphi, Rebecca Kariuki, Aziza Nchimbi, Tahir Haji, Irene Musa, Sam Buckton, Ioan Fazey, Suzanne Om, Charis Enns and Robert Marchant provided guidance and commented on drafts.

Publications:

Chapter 1

The conceptual framework of the PhD was written by Rebecca Newman with the guidance and support of all co-authors and published in *Sustainability*. Within this thesis the original article was edited to focus more on the background rationale and emergence of the conceptual framework with its application being more thoroughly explained in the following chapters.

Newman, R. J. S., Capitani, C., Courtney-Mustaphi, C., Thorn, J. P. R., Kariuki, R., Enns, C., & Marchant, R. (2020). Integrating Insights from Social-Ecological Interactions into Sustainable Land Use Change Scenarios for Small Islands in the Western Indian Ocean. *Sustainability*, 12(4), 1340. https://doi.org/10.3390/su12041340

Chapter 2

The first stage of research was a scoping study to test the appropriateness of the conceptual framework, build trusting relationships with communities and inform the planning for the next phases of the project. The focus group findings were written up as a journal article by Rebecca Newman with the support and guidance of co-authors and published in *Population and Environment*. The chapter remains the same as the final edit of the publication.

Newman, R., Thorn, J., Nchimbi, A. Y., Musa, I. K., Enns, C., Marchant, R., & Haji, T. A. (2023). A people-centred framework for exploring water, energy and food security in a small developing island. *Population and Environment*, 45(3). https://doi.org/10.1007/s11111-023-00427-2

Chapter 3

Following on from insights gleaned from the focus group work, community-based workshops were undertaken across the same 10 villages. In these workshops a deeper understanding was sought with regards to how the landscape has changed, why this has happened and what the implications are for water-energy-food security. Reflecting on emerging and persistent challenges for specific types of land cover transitions, participants began to suggest strategies for remediation. This research was written as a journal article by Rebecca Newman, with the support and guidance of co-authors and published in *Sustainability Science*.

Newman, R.J.S., Capitani, C., Enns, C. Marchant, R. (2024). Community-centred scenarios development for water–energy–food security on Zanzibar. *Sustainability Science*. https://doi.org/10.1007/s11625-023-01443-9

Chapter 4

This final data chapter integrates local knowledge concerning drivers of land cover and land use change with expert knowledge from key government and third sector organisations. In a one-day workshop, participants worked together to develop scenario narratives of future land cover changes based on themes generated from the community-based workshops. Workshop participants were asked to make predictions about how these might shape land cover and ultimately resource security in terms of the water-energy-food nexus.

Newman, R.J.S.; Enns, C.; Capitani, C.; Thorn, J.P.R.; Courtney-Mustaphi, C.J.; Buckton, S.J.; Om, E.S.; Fazey, I.; Haji, T.A.; Nchimbi, A.Y.; et al. (2024). 'Kesho' Scenario Development for Supporting Water-Energy Food Security under Future Conditions in Zanzibar. *Land* , 13, 195. https://doi.org/10.3390/land13020195

CONTENTS

Figures and tables

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Whilst studying in Zanzibar I met some great collaborators who provided support operationally, including Tahir Haji and Aziza Nchimbi from the Department of Forestry and Renewable and Non-Renewable Resources in Unguja and Muhena in Pemba. As well as Kassim Madeweya, the director of the forestry department at the time.

Special thanks go to all the community members and representatives from NGO’s and government departments who contributed to the research process. I learnt so much and had a wonderful experience visiting and working with people from many different villages within Unguja and Pemba. In Pete the community gave a Swahili name, Hidaya, meaning gift - which was a great honour.

During my fieldwork in Zanzibar, I met my husband Khamis Fakih, who I now share two beautiful children with, Esme born in 2020 and Amir in 2022. I would like to thank them for their understanding and support while balancing family life with studies. Khamis and I raised both children on the east coast of Unguja island for their early childhoods , a very special time.

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I would also like to pay special thanks to the Economic and Social Research Council who funded my PhD and the Black Heart Scholar Foundation for supporting me with personal finances whilst I completed my studies.

INTRODUCTION

BACKGROUND

Small islands in the global south face several environmental challenges which impact resource security (Poti et al., 2022). They are exposed to greater tropical and extratropical cyclone frequency and intensity, increased sea and air temperatures, variable rainfall patterns and sea level rise (IPBES, 2018; Duvat et al, 2017; Mycoo et al., 2022). Alongside this, there are competing demands on land use from tourism and population growth (Adger et al., 2009; Crisman & Winters, 2023); which further contributes to sustainability challenges, such as the degradation of forests (Barbier, 2015), pollution of water courses (Hernández-Delgado, 2015) and unsustainable intensification of agriculture (Suckall et al., 2014). These pressures are particularly intense in small islands due to their size, geographical isolation, and low lying topography (Pelling and Uitto, 2001; Pomeroy et al., 2006). The combined impacts of these factors are likely to impair ecosystem function, compromise resource security, public health, local economies, and people's livelihood sustainability (Hernández-Delgado, 2015).

Effective land use and land cover planning is needed to ensure long-term environmental sustainability in small islands (Hugè et al., 2018). Participatory scenarios planning can be used to explore multiple and interacting pressures alongside their implications for land use futures (Kariuki et al., 2022; Capitani et al., 2016). The collaborative process fosters multiscale social learning and an appreciation of the complexity of interactions with landscapes for different stakeholders. This can help to sensitise the perspectives and needs of different stakeholders across scales and ideally helps to strengthen understanding between stakeholders and promote inclusivity within scenarios design (Kok et al., 2007; Johnson et al., 2012; Malinga et al., 2013). However, community scale involvement is still limited in participatory processes due to barriers such as gender, poverty, poor education, and a lack of accessible information (Gustavsson et al., 2014; Kwayu et al., 2014). Consequently, there is often poor representation of the knowledge and needs of local communities in sustainable land use planning (Fagerholm & Käyhkö, 2009).

As people living on small islands often have close social-ecological relationships, through both their livelihood activities (i.e., fishing, farming, seaweed farming, livestock keeping) (de Jong Cleyndert et al., 2021; Kukkonen and Käyhkö, 2014; Suckall et al., 2014) and ways of obtaining their basic resources (i.e., fuelwood, water from oases and wells, subsistence farming), they have a substantive influence on land use and land cover through their interactions (Douglas, 2006). But these interactions are changing due to multiple reasons, and often it is these dynamic changes in social-ecological relationships that are missing from conceptualisations of sustainability in land use and land cover scenarios. Diverse participation in scenario development helps to ensure that decisions towards sustainability better reflect plurality and contextuality – thereby facilitating greater appropriateness and inclusivity (Lala et al., 2023). Despite this recognition there is still a serious lack of participatory scenarios research in small islands generally, with limited examples focused on Europe (Royuela et al., 2016; Drakes et al., 2020). If scenarios are to effectively capture social-ecological responses, then the explorative framework needs to work at the functional boundary between people and their environment. One way of doing this is through exploring resource use and management, such as water, energy and food.

Increasingly, the water-energy-food nexus has been suggested as a useful lens to explore interrelated dynamics between people and the natural environment (Biggs et al., 2015). The water-energy-food nexus seeks to understand the interdependency, synergies, conflicts and trade-offs between water, energy, and food (Martin del Campo et al., 2023). Whilst the water-energy-food nexus has a human needs focus, research in this field has tended to operate at systems level and lacks in integration of qualitative aspects (Crisman and Winters, 2023). Planning towards sustainable development requires an explicit focus on the livelihood dynamics within nexus framings to capture bottom-up approaches and local opportunities for sustainable development (Biggs et al., 2015). By recognising the interplay between resource extraction and livelihoods, the intersection between environment and justice can be better acknowledged in policies aimed at supporting sustainability (Dean, 2023).

The thesis's core focus is to create sustainable land use scenarios to support water-energy-food security through embedding an understanding of interactions between people and their environment. To develop robust and appropriate scenario alternatives, conceptually it becomes important to understand sustainability in a way that appreciates social and environmental outcomes across temporal and spatial scales. Empirically, the nature of community engagement is also critical, and requires a considered research approach that is sensitive to barriers to inclusion and effectively facilitates diverse engagement. Consequently, the thesis begins with a conceptual exploration of how to approach investigating sustainable social-ecological relationships in small islands. It then goes on to present insights from village leaders and elders about responses to change and how these reshape social-ecological relationships for water-energy-food security. Following this, critical reflections from a community perspective about land use and land cover changes and water-energy-food outcomes are presented. These insights are then applied in multistakeholder scenarios workshops to create robust narratives for change that would support water-energy-food security.

Aim

To develop robust participatory sustainable land use scenarios which support water-energy-food security in a small island context by integrating insights about people's responses to change across temporal and spatial scales

Objectives

(1) Understand how people interact with their environment to meet their water-energy-food needs across diverse land cover types

(2) Explore how social-ecological change influences land use and land cover and the implications of this for water-energy-food security

(3) Develop socially appropriate place-based sustainable land use scenarios which have the capacity to support water-energy-food security

Case study site

Zanzibar was chosen as a case study site for several reasons. Like Small Island Developing States (SIDS), it has a small land mass, high levels of tourism, reliance on external markets and a narrow resource base – all of which make Zanzibar vulnerable to biodiversity loss and climate change. However, because of its semi-autonomous relationship with Tanzania, it is not considered within SIDS research. In fact, in general, research into sustainability in small islands is largely representative of the Caribbean, meaning there is a lack of understanding about islands in the Western Indian Ocean (Poti et al., 2022).

Zanzibar also offers a unique opportunity to explore the differential opportunities and challenges that alternative socio-economic trajectories have on land use and land cover. The island of Unguja is a well-known hotspot for tourism attracting upwards of 300,000 international visitors annually (Office of the Chief Statistician of Zanzibar (OCGS), 2024). Zanzibar town (Stonetown) has been granted international recognition with its cultural heritage status (United Nations Educational, Scientific and Cultural Organization (UNESCO), 2000). Pemba has a considerably lower rate of tourism and is more famously known for clove trade (OCGS, 2015). Despite the differences between the two islands, most research in Zanzibar itself focuses only on Unguja.

Like many small developing islands Zanzibar is experiencing challenges related to climate change and sea level rise. As many people develop a livelihood from a portfolio of activities they can suffer from interrelated shocks and stresses; for instance, prolonged dry spells and variable rainfall affecting small scale agriculture, increased sea temperatures increasing seaweed disease and reductions in fish catch (Makame et al., 2023). Poverty is a central concern with household size and education level shown to be predeterminate influences on poverty (Makame & Mzee, 2014). Rapid land use and land cover change is also impacting important ecosystems which people rely on to meet their livelihood needs (Nchimbi & Lyimo, 2019).

As well as connecting to many issues which are displayed across other small developing islands, Zanzibar has potentially unique characteristics which relate to its historical connection to the slave trade and its mix of Islamic, Swahili and Bantu culture. Zanzibar was under colonial rule from the Portuguese for two centuries, during this time they gained international connections through the trade of ivory, slaves and cloves (Croucher, 2011; Myers, 2012). In 1698 Zanzibar became under Omani rule until 1860 when it came under British Colonial rule. In 1963 Zanzibar gained independence and the People's Republic of Zanzibar was formed. However, soon after this a formal union was made with Tanzania (Myers, 2012).

Zanzibar retains many of its Arab, Indian, and European influences, but also retains its indigenous elements, to form an urban cultural unit unique to this region (UNESCO), 2000). Therefore, as well as being a useful case study in the context of small islands, it also offers an opportunity to understand place specific factors that may shape people's social-ecological interactions at the community level.

Positionality

This research aimed to facilitate a more equitable dialogue to inform sustainable land use scenarios to support water-energy-food security in Zanzibar. Consequently, there are several dimensions regarding positionality that needed consideration during the research process. From the onset of a project, the topic itself might originate primarily from the researcher either because of their perceived understanding of research gaps or personal interests (Secules et al., 2021). My personal interests centred on understanding social-ecological responses to change. The nexus framing for exploring those interactions came from the Bonn 2011 Nexus conference which presented evidence on how a water-energy-food nexus approach can help increase resource security by reducing trade-offs and building synergies (Hoff, 2011). My decision to focus on the community scale was strengthened by the recognition that community scale insights were largely absent from nexus research (Biggs et al., 2015). I spent six months in Zanzibar whilst writing the conceptual framework of the thesis. This allowed me to observe existing and emerging social-ecological changes for the water-energy-food nexus and confirm its potential usefulness for helping to inform land use decisions. Whilst I tried to ensure that it had contextual appropriateness, I must state that the framing emerged from my own observations and perceptions.

The second dimension of positionality that required careful consideration was that of power. Firstly, there is the question of how I would be perceived, as a researcher from the United Kingdom, coming to Zanzibar to explore sustainability challenges. This can be problematic for several reasons, dating back to colonialism, but also decades of the assumption that it takes outside influence to 'solve' development issues in African contexts (Smith, 2012; Thambinathan & Kinsella, 2021). I attempted to overcome this in several ways, firstly, I learnt and respected due processes for establishing relationships with the community. This involved learning basic Swahili, visiting the village leaders to introduce myself and then set up the research process so that communities had a sense of ownership. For instance, the village leaders and elders gave input on the structure of the day and activities. They also chose the location and were given a budget to organise catering and venues. Participants expressed that they felt they were hosting us, which helped to shift the perceptions of power a little. I also worked with Zanzibari facilitators, who were very skilled in providing an inclusive and relaxed environment which stimulated a great level of engagement.

Another factor to consider is the role of the researcher and the purpose of the research itself. One of the key aspects of this research was trying to integrate local community insights into land use scenarios so that they better reflected what they needed from landscapes. This aim could however imply that communities are not able to share their voice without the researcher, and therefore assume 'disempowerment' (Thambinathan & Kinsella, 2021). I knew that I did not have the capacity to 'empower' people, so I tried to be clear about that. When introducing the research process I explained that I was a researcher doing my PhD and was interested in learning from communities and integrating these insights into planning for a sustainable future. I was transparent in saying that I had no decision making power about land use in Zanzibar, but that I would communicate findings and hope that they would be reflected on by those who do. Participants responded by wishing me luck with my studies and said that they were happy to help me, which to me felt like they were aware that they held power through their experience and knowledge.

As well as giving forethought to issues of positionality, it was also important to be reflexive throughout the fieldwork and data analysis process (Ellis and Berger, 2002). Transparency and trustworthiness are integral to collecting data that is true to the circumstance being studied (Adeagbo, 2021). To achieve this, the researcher must reach across ethnic, racial, economic and gender boundaries (Neuman and Neumann, 2015). This requires continuous reflection on the status or identities of a researcher and how these may influence the research process (Buscatto, 2016). I was working in a traditionally patriarchal society, but in a time where gender balance was increasingly being advocated for. That meant that I had to find a balance between observing embedded societal rules (i.e., not shaking hands with men or making direct eye contact) whilst also recognising that shifts in ideas were happening in this arena. For this, I took advice from researchers with a long history of community-based work in Zanzibar as well as my fieldwork facilitators.

One of my initial assumptions was that I would need to speak with men and women separately, but my Zanzibari facilitators said "*no, women in Zanzibar have no problem expressing themselves*" and were slightly offended by my suggestion that they might be disempowered in a mixed gender workshop. Because the topic was about resources, which is usually navigated on a household level, it seemed appropriate then to have a more integrated approach, involving all genders and age groups. At the same time, the advice came from an educated woman, who was in a well-respected position – so perhaps did not experience the same realities as some of the women in rural settings. Whilst collaboration appeared to be meaningful in the focus groups and workshops, more consideration could have been given to the nuances of intersectional livelihood dynamics, and how this might impact participatory discussions in relation to resource security (Smith et al., 2023).

Continuous reflexivity is needed as researchers' identities are subject to change during the research process; this can be especially true if the research has a long duration (Roberts, 2018). I certainly had that experience, initially coming into my study area as an outside observer, I then met my partner, who is from Zanzibar, had two children (both with dual citizenship), and moved to a rural village on the coast. I experienced the frustrations of lengthy unplanned power cuts and distributions in water supply. We had to also revert to using well water and faced subsequent health related challenges. But whilst we experienced these resource challenges, we had different capabilities which meant we could respond to them more easily than others. I realised I could never fully understand how challenging it was for households to navigate these perturbations in resource security. I also realised that resilience is more than physical capabilities, it extends also to a strength of character, culture, and faith – which are not particularly acknowledged in my research.

This transition from being an outsider, to an insider in some degree I expect impacted the interpretation of my results (Shaw et al., 2020). However, rather than seeing these changes as a challenge for objectivity or consistency in approach, they likely convey a greater depth of understanding of the context (Adeagbo, 2020). That said, having the experience I have had, there are many things I would consider approaching differently in the future – of which I discuss in the concluding chapter.

STRUCTURE OF THE THESIS

Chapter 1

Chapter one reviews the sustainability challenges for small islands and how ideas for sustainability need to allow for more dynamic interactions across spatial and temporal scales. It presents the conceptual framework for the thesis, which considers water-energy-food security to be influenced by people's reactive or proactive responses to environmental and social change.

Chapter 2

Chapter two forms the scoping study for the thesis, in which the conceptual framework is trialled. Semi-structured focus groups were undertaken with village leaders and elders (men = 23; women = 17). Findings unveiled shocks and stresses pertinent to different land cover types alongside their impacts on water-energy-food security. They also gave insights into how people respond to shocks and stresses and levers and barriers that mediate such responses.

Chapter 3

Chapter three explores the relationship between people and land through a water-energy-food nexus lens to identify key land cover transitions which have, or are expected to affect resource security and livelihoods and develop themes for sustainable land use scenario alternatives. This involved 10 community based workshops (men = 77 ; women = 65). Participants identified key drivers of land use and land cover change and discussed which drivers would be most significant by the year 2030. They also evaluated their water-energy-food security under past conditions (20 years prior to the workshop) and present day (year 2019). They discussed specific challenges for land use and land cover and communicated their recommendations for remediation.

Chapter 4

Chapter four presents alternative scenarios for sustainable land use in Pemba and Unguja islands, which were developed through multi-stakeholder scenarios workshops (men = 39; women = 28). In these workshops participants explored how key drivers of change operate spatially and temporally and developed alternative scenario narratives using themes generated at the community scale. Finding revealed emergent vulnerabilities for resource security, specific hotspots in both islands where impacts from drivers of change would be most observed and predictions for land use and land cover by 2030 alongside their implications for water-energy-food security.

Chapter 5

Chapter five draws out the empirical contribution that the thesis makes, in relation to Zanzibar's land use consideration and small islands in general. It also comments on the conceptual and methodological contribution and key lessons learnt through the research process. Reflections are also made with regards to how findings from this thesis relate to more recent work on the topics of participatory scenarios and the water-energy-food nexus in small islands.

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1 CONCEPTUAL FRAMEWORK: INTEGRATING SUSTAINABILITY PERSPECTIVES TO UNDERSTAND SUSTAINABILITY CHALLENGES AND OPPORTUNITIES IN A SMALL ISLAND CONTEXT

ABSTRACT

Small islands are vulnerable to synergistic effects of climate change and anthropogenic disturbances due to their small area, geographical isolation, responsive ecologies, rapidly growing and developing populations and exposure to sea level and climate change. These changes exert pressures on ecosystem services, such as the provisioning of resources, and therefore threaten the sustainability of livelihoods. Given the interconnections between water-energy-food, a nexus approach is increasingly recognized as a useful strategy to explore the effects of environmental change on small islands and develop holistic solutions to sustainability challenges. To date there has been a lack of integration of local community insights and experiences within water-energy-food nexus research. Despite this, such an exploration is crucial for understanding evolving social-ecological and ecosystem services interactions over time. In this article, key sustainability and livelihoods literature are reviewed to bring together concepts of environmental livelihood resilience and stability across temporal and spatial scales. These are integrated into a conceptual framework for *Environmental Livelihood Sustainability* (ESL), which aims to facilitate the incorporation of local community perspectives into water-energy-food nexus thinking about sustainable land use to support local livelihoods. This framework could be applied to sustainable land planning to facilitate community needs and insights into the future. It also provides a mechanism for enhancing the agency of communities to produce more cohesive and inclusive land use management plans that can lead to enhanced environmental sustainability options.

Keywords: climate change; decision-making; human-wellbeing; nexus; participatory methods; poverty alleviation, Zanzibar

BACKGROUND

With significant environmental and social pressures impacting the sustainability of current social-ecological systems there are several efforts to bring people together through participatory processes to plan ways to tackle challenges and promote more sustainable systems. Recognising the tight dynamics between people and environments there is a need to adequately recognise how change impacts the ways in which people navigate their environments to meet their needs.

This article brings together principles from different ways of thinking about sustainability to create a dynamic framework which could be applied to participatory scenario processes. In the sections that follow sustainability ideas are explored and integrated to produce a conceptual framework which was used to guide the research design of the thesis.

Sustainability challenges for small islands

Small islands in the Global South are being challenged by several social and environmental pressures, including population increase and rapid economic growth, leading to unplanned urban development, inadequate governance structures, sea-level rise and climate change (IPCC, 2014; IPBES, 2018). In small islands, population growth – from both external and internal migration – has concentrated in coastal areas (Neumann et al., 2015). Tropical coastal areas are experiencing rapid economic and natural resource management changes with the rise of tourism infrastructure development (Adger, 2009; Saunders et al., 2010). Such competing land uses can lead to conflicts between communities and other land users; for instance, some hotels restrict access from the village to the beach. Seaweed farmers are also often asked not to dry the seaweed in view of hotels and in some areas coastal access has been limited using security enforcement. Seasonal tourism also increases stress on limited water resources during dry seasons (Hampton & Jeyacheya, 2015).

Land use and land cover change also has a significant bearing on the scale at which climate change impacts will be felt by decreasing the capacity of natural capital to buffer communities against chronic and acute environmental perturbations (Capitani et al., 2019). For instance, reductions in shoreline vegetation (especially mangrove and coastal forest) mean that there are fewer natural defences against seawater intrusion, leading to soil erosion and a lower water infiltration capacity. Because of this, coastal zones are disproportionately vulnerable to climate changes and are likely to experience a high level of multiple and interrelated climate risks with a subsequent consequence on economies (IPCC, 2018). As key supportive ecosystems of low-lying coastal areas and small islands continue to be removed or degraded, protection from acute natural disasters (such as flood inundation and storm surges, and long-term changes such as sea level rise, saline intrusion, submergence, and coastal erosion) will decline (Barbier et al., 2015; IPBES, 2018). Such impacts are likely to have cascading implications for water-energy-food security and thus, the sustainability of livelihoods.

The framework outlined by the Paris Climate Change Agreement in 2015 sets out to strengthen society's ability to adapt to impacts of climate change and build resilience at national level. Targets set out within the Sustainable Development Goals (SDG) also seek to support the sustainable management of ecosystems (SDG 15), alleviate poverty (SDG 1) and increase the capacity of vulnerable people to respond to climate change impacts (SDG 13). Although such policies are interconnected, pressures related to these targets have often been addressed separately, at times reducing one problem, while exacerbating another (Liu et al., 2018).

Implications of environmental and socio-economic changes for local livelihoods on small Islands

Rural livelihood activities on small island settings often depend upon natural resource use and are underpinned by provisioning ecosystem services (Suckall et al., 2014; Khamis et al., 2017; Nunn & Kumar, 2018). Coastal environments on small islands such as Zanzibar have traditionally supported deep-water fishing, bivalve collection, octopus fishing in shallow waters, aquaculture and, more recently, seaweed and sponge farming (Khamis et al., 2017). Island communities also highly depend upon coral reefs and mangrove ecosystems for coastal protection, subsistence fisheries and tourism (Adger, 2009). In contrast, inland spaces have been typically used for smallholder farming, rice paddies, agroforestry and timber extraction (Suckall et al., 2014; Khamis et al., 2017; Connell et al., 2020).

Climate change negatively impacts livelihoods across both coastal and inland spaces. Changes in precipitation negatively impact smallholder farming livelihoods through less predictable planting times, unreliable harvests, increases in soil erosion and plant pest and disease outbreaks (Patz et al., 2000; Suckall et al., 2014). Sea temperature rises are causing coral bleaching and reef degradation with impacts on associated livelihoods (i.e., fishing, seaweed farming and reef excursions for tourism) (Suckall et al., 2014).

As well as climate change and variability, other common drivers of change on small islands impact local livelihoods and supporting ecosystems. For instance, international fluctuations in market prices affect agricultural planting decisions in terms of timing, economic returns, and crop type choices (Risbey et al., 1999). Farming space is typically limited on small islands and market fluctuations are likely to have significant economic and food security impacts (Connell, 2014). Changes to forest legislation, such as the gazettement of protected areas, alter forest use and can shift deforestation to other areas (Ewers & Rodrigues, 2008). Mangrove deforestation has led to a reduction in coastal protection and other ecosystem services, particularly fish nurseries and timber (Alongi, 2002). The expansion of tourism has caused reduced shoreline vegetation, overextraction of timber and rubble and a greater exposure to the effects of sea-level rise (Mustelin et al., 2010; Peña-Arancibia et al., 2019). Tourism-related activities, such as windsurfing and snorkelling, have also altered the ways in which the coastal spaces are being used, at times causing land use conflicts (i.e. between kite surfers and seaweed farmers, fishermen and snorkelling excursions, hoteliers and women collecting bivalves) (Lange, 2015).

More broadly, population growth has also been thought to increase pressure on fisheries, competition for farming land, relative food prices and firewood availability, with the subsequent degradation of ecosystem services (Cinner et al., 2012; Shiferaw et al., 2014; Hampton and Jeyacheya, 2015). In addition, population growth is connected to increased requirements for wastewater treatment and can lead to pollution from nutrient loading if these needs are not met (i.e., from solid waste which is disposed of in sink pits).

Whilst these drivers leave small islands highly vulnerable, there are also some island specific opportunities to be taken into consideration. For instance, though geographically isolated, islands often have deep maritime connections that enhance their import-export capacity (Crowther et al., 2016). Strong cultural identities and social networks within small islands also enhance peoples' ability to adapt to shocks and stresses, as connectedness increases capacity for collective or shared action (Adger, 2009; Petzold & Ratter, 2015).

Moreover, whilst the expansion of tourism has implications for sustainable land use, there are some economic benefits to local communities in the form of formal and informal employment (Sharpley & Ussi, 2014). Higher rates of employment and development can lead to increased access to higher education of younger generations and a transition from subsistence lifestyles to income-generating activities such as working in service sectors and government offices. Road infrastructure networks also improve the connectedness between rural and urban spaces, improving mobility and market access.

It is also worth noting that, despite population growth being emphasised above as a threat to environmental sustainability in small islands, there are opposing arguments for this which challenge the concept that it has adverse impacts. For instance, Leach and Fairhead (2001) point to examples of innovations and technological improvements that have reduced population pressure on land and improved living conditions in Africa, even as populations have grown.

Overall it must also be recognised that because of the physical characteristics of small islands, they are vulnerable to multiple stressors, including both climate and non-climate related. Therefore, climate change needs to be tackled in a multidimensional way, addressing drivers of environmental degradation alongside climate impacts (IPCC, 2014). Considering the complexity of changes, planning for future environmental sustainability on small islands in the Western Indian Ocean needs to consider how drivers of change are reshaping the social-ecological relationships within those environments at different scales to better identify emerging vulnerabilities and opportunities for local livelihoods.

Concepts for exploring social-ecological dynamics in small island contexts

Sustainable Livelihoods Approach

Environmental sustainability depends upon a balance between maintaining the capacity of ecosystems, whilst also satisfying the needs of society (Morelli, 2011). This definition builds upon recognition that landscapes are multifunctional; within these landscapes, social-ecological relationships are shaped by the needs of different stakeholders (Marchant et al., 2016. This approach differs from early environmental sustainability thinking, which saw social and environmental systems as distinct and separate (Berkhout et al., 2003). In light of these developments, various frameworks have been developed to illustrate how the social and natural components of sustainability are linked through people's behaviours (Kate et al., 2001).

For decades now, the Sustainable Livelihoods Approach (SLA) (Figure 1) has provided a mechanism for exploring interactions between humans and their environment and has been used to assess vulnerability, adaptability, and resilience by linking to both environmental and socio-economic concerns (Biggs et al., 2015). The Sustainable Livelihoods Framework, developed by Scoones (1998), recognised that natural resource capital contributes to rural livelihoods and that environmental stresses modify livelihood stability and augment vulnerability and opportunities for rural communities (Chambers & Conway, 1992). It was also accepted that social-ecological interactions may then change in response to environmental stresses, thereby causing further environmental degradation as people continue to meet their livelihood needs (Barbier, 2015). In doing so it touched on ecosystem service concepts, whereby the ecological system is interpreted through the lens of benefits to humans.

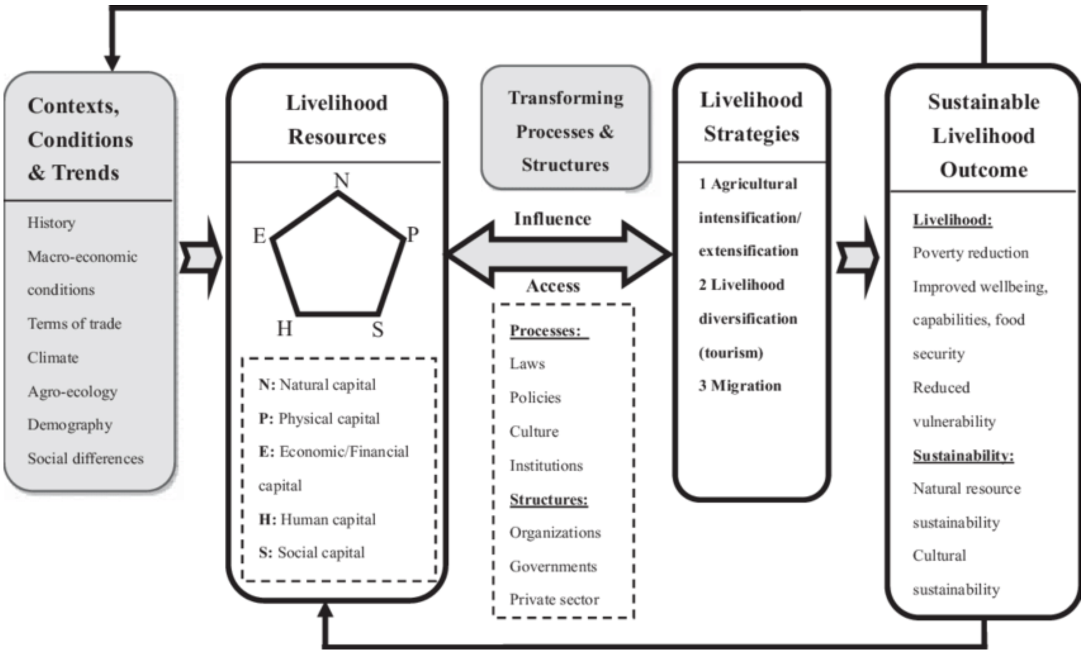

Figure 1. Sustainable Livelihoods Approach by Scoones (1998) derived from DIFID (1999).

It has more recently been argued that links between livelihoods and ecosystems as reflected by the SLA have been overly simplified and that it fails to capture the complexity of socio-ecological interactions. Whilst the SLA provides valuable insights into how rural communities are connected to their environments, it only depicts these relationships in a bounded sense (direct explicit relationships) and does not account for dynamic longer-term changes, such as those related to agrarian change or systematic transformations resulting from socio-political demographic, ecological succession, or climatic variability and change (Scoones, 2009; Biggs et al., 2015). Similarly, sustainable livelihoods theory does not sufficiently disentangle global influences on local livelihood dynamics or connect locally embedded contexts to wider global economic and climatic changes. As such, this approach risks providing a lack of understanding about global influences on human-environmental relationships overall (Scoones, 2009; Leach et al, 2010).

With a growing recognition of these limitations, more recent frameworks attempt to pay more attention to socio-ecological interactions across time and space, including local and global level interactions that shape human and natural systems (Carter et al. 2014, Liu et al., 2018). For example, the traditional sustainable livelihoods framework takes temporality into account by exploring the effects of shocks (short term perturbations) and stresses (longer term changes) on the stability of livelihood outcomes (Scoones, 1998; Chambers & Conway, 1992). Within the SLA, sustainability is centred on the theory of stability (Chambers, Glasgow & Strange, 2013). However, Leach et al. (2010) argue that stability-focused narratives on sustainability fail to acknowledge external, longer term and less controllable dynamics (i.e. global influences and external pressures).

Principles from the SLA have been brought into adapted framings that more explicitly demonstrate the complex nature of social-ecological change resulting from the combined effects of population increase, socio-economic development and rapid environmental changes. At the same time, the water-energy-food (WEF) nexus approach has gained increasing attention within research and policy dialogue, as it has become increasingly clear that the resources that support environmental sustainability and sustainable livelihoods are inextricably linked, as are their vulnerability to climate change (Bazilian et al., 2011; Leck et al., 2015). Fürst et al. (2017) propose embedding ecosystem service concepts into such nexus approaches.

Dynamic sustainability

In response to the limitations of the SLA approach, Leach et al. (2010) developed a dynamic framing of sustainability which focuses on stability, resilience, durability, and robustness and how these actions interact across temporal scales to achieve sustainability (Figure 2). In addition to the temporality of change, attention is also given to styles of action; specifically, whether the aim is to control or respond to shocks and stresses. This framing builds on traditional stability focused narratives by incorporating ideas related to resilience. Resilience goes beyond stability concepts as it describes an ability to recover from and reorganise in response to disturbances and increase adaptive capacity for responding to shocks and stresses (Krueger et al., 2022). Planning for resilience then centres on building capacity to sustain when faced with change, and therefore becomes a dynamic concept concerned with navigating complexity and uncertainty (Folke, 2016). Resilience however assumes persistence within current system boundaries and adaptive capacity within those. therefore to some extent resilience focused planning does not necessarily open up discussions around wider system change that might be needed, but more what can practically be achieved given current parameters (Krueger et al., 2022).

A dynamic sustainability framing could provide a more proactive approach for the illumination of adaptation pathways within given system boundaries. Leach et al (2010) used these components of dynamic sustainability within a governance and social justice framing and applied them to the context of managing disease epidemics. This concept of dynamic sustainability could be used to explore how financial, natural, human, physical and social capital shape the capacity of a person or community's dynamic sustainability (Scoones, 1998; Chambers and Conway, 1992' Berkout et al., 2003). Learning about these interactions and what governs them is fundamental to understanding how drivers of change shape social-ecological relationships (Speigelberg et al., 2017) and thus land use and land cover patterns (Capitani et al., 2016). Linking together insights around changes in social-ecological relationships with the emerging consequences for ecosystem function means that resilience theory, which focuses on ecological interactions and their implications for the biosphere, can also be incorporated (Folke et al., 2016). Vulnerable social groups could also be identified by assessing the capacity of different groups to utilise different response strategies to achieve dynamic sustainability, which will be especially useful toward addressing poverty alleviation agendas such as the SDGs (UN, 2015).

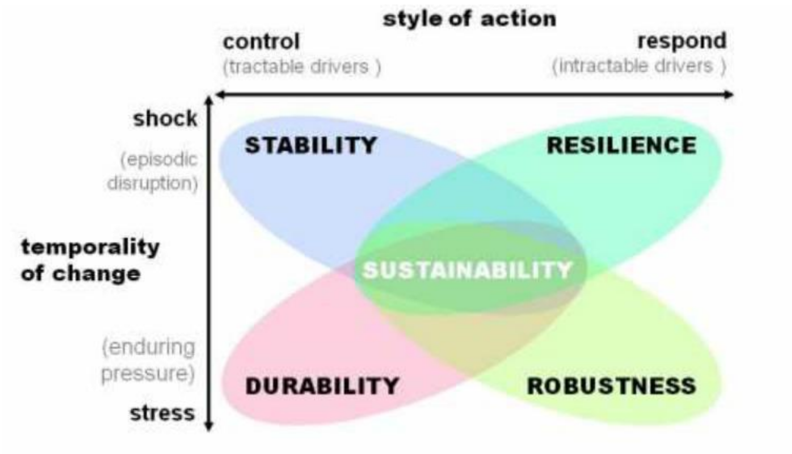

Figure 2. Framework for dynamic sustainability by Leach et al (2010).

Water-energy-food nexus approach

Recognising that people are inextricably linked to their environment through livelihoods, and consequently the importance of capturing human-environment interactions in sustainability research, Biggs et al. (2015) developed an integrative framework combining principles of the SLA with insights from WEF nexus thinking. This framework aims to assess the environmental security of livelihoods across whole systems and multiple scales (Figure 3). In this case, 'Environmental livelihood security', refers to the ability to maintain adequate water, food and energy security to meet people's livelihood needs whilst also supporting economic growth and sustaining environmental system functionality (Biggs et al., 2015). The framework assesses interactions between a given livelihood activity and the landscape; for instance, it has been used to explore potential impacts of climate adaptation interventions in agriculture (Biggs et al., 2014).

Resource limitations in small islands and interactions between climate change, sustainable livelihoods and the WEF nexus are important to consider. Within small islands, communities often undertake a diverse range of livelihood activities which draw upon water, energy, and food resources (Suckall et al., 2014). Whilst the Biggs et al (2014) framework demonstrates the capacity to cover differences in environmental conditions across spatial scales and economic sectors, there is also a need to interrogate changes over retrospective and future-oriented temporal scales.

Within multifunctional landscapes, rapid socio-economic, demographic, and environmental changes have implications for land use and land cover that ultimately impact upon the security of water, energy and food (Bazilian et al. 2011; Leck et al., 2015; Liu et al., 2018). Understanding the impacts of these drivers of change requires some reflection on how they have altered the sustainability of landscapes so far (Marchant et al., 2016). Due to the rapid nature of environmental change in small islands, temporality is a particularly important aspect to consider.

Nexus approaches to conceptualising sustainability also have both strengths and weaknesses. Leck et al (2015) propose that applying nexus approaches facilitates greater communication between natural sciences and social sciences. Liu et al (2018) further state that nexus-oriented methods can provide a forum for bringing together diverse actors from different sectors to support the development of more coherent policies.

This said, to date, nexus studies have tended to adopt broad scale systematic approaches that fail to integrate both theoretical and applied insights (Leck et al., 2015; Engler et al., 2018). As a result, these approaches do not fully cover the complex nature of social-ecological interactions within locally embedded contexts. Therefore, thought needs to be given not only providing a framework which facilitates local knowledge exploration, but also the processes by which this is undertaken (Berkhout et al., 2003).

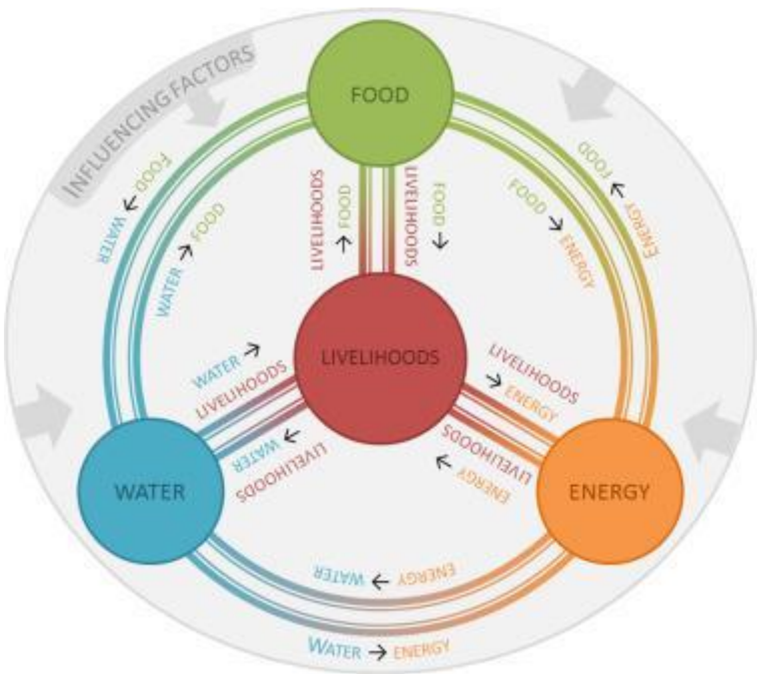

Figure 3. The environmental livelihood security framework by Biggs et al (2014).

INTEGRATING CONCEPTS THROUGH PARTICIPATORY SCENARIOS PROCESSES

In recognition of the complex interactions between social and natural drivers of environmental change, there has been a call for more integrated approaches to exploring environmental change and enhancing resilience (Bazilian et al., 2011). Leach et al. (2010) state that responding effectively to environmental and developmental challenges involves observing the interactions of different system components at multiple scales. Sherman et al (2016) further states that planned adaptation and transformative change within developing economies relies upon diverse sources which test multiple framings of adaptation and development. As environmental sustainability depends upon interactions between local and global processes, as well as the ecological and social characteristics of places and sectors, there is a need for more multidisciplinary approaches to tackle challenges (Kate et al., 2001). Liu et al (2018) agree that new integrated approaches are needed to manage challenges created by multiple, and at times conflicting, human needs and demands to reduce poverty and promote sustainability.

In response to this need, recent studies have advocated for a multiscale participatory approach to development discourses about sustainable livelihoods (Capitani et al., 2016; Coleman et al., 2017; Kebede et al., 2018). Many researchers also discuss the importance of capturing and exploring local people's experiences and expectations when exploring climate change adaptation (Fagerholm et al., 2012; Savo et al., 2016; Cuni-Sanchez et al., 2018; Goldman et al., 2018; Thorn, 2019).). Scenario methodologies can be used to identify potential integrated sustainability challenges for the future (Capitani et al., 2016; Kowalski et al., 2009). The collaborative process of scenario development can help support multiscale social learning and sensitise participants to the perspectives and needs of stakeholders at different scales (Kok et al., 2007; Johnson et al., 2012; Oteros-Rozas, 2015; Kariuki et al., 2021).

Land is an important lens for which these relationships can be explored as social-ecological relationships occur in place and often mediate and alter landscapes, which in turn shape future social-ecological relationships. In this article the concept of land futures is used to explore the sustainability of water-energy-food. There are scenario approaches which focus explicitly on agent-based narrative development to recognise human-environment interactions (González-Méndez et al., 2021). Alongside this recognition that human-environment interactions shape land use, land cover modelling processes have also attempted to ingrate qualitative data to legitimise outputs (ie. Gome et al., 2020; Rivas-Tabares et al., 2022). These methodologies often use qualitative and quantitative data though a coupling approach, which may limit the agency of stakeholders in the actual modelling process. In recognition of this, an alternative approach was developed to for scenario development which provides a more integrative and iterative approach to land cover modelling – which was later developed into a tool called Kesho (“tomorrow” in Swahili) (Capitani et al. 2019; Resilience in East African Landscapes (REAL), 2024).

Kesho is essentially a participatory framework which was developed to support multi-stakeholder engagement in a land use and land cover framework. It consists of four main steps that involve experts (facilitators) and stakeholders (those who are affected by or can affect socio-economic and land dynamics): 1) scenarios setting; 2) stakeholder-driven scenario development; 3) modelling; 4) synthesis, feedback and consensus building (Capitani et al., 2019). Because of its key principles of inclusivity and iteration, the Kesho framework provides a mechanism for unifying concepts of dynamic sustainability and environmental livelihood security (Table 1).

Table 1. Description of key existing frameworks for sustainability, their previous applications and identified gaps in terms of their capacity to integrate livelihood impacts and sustainable land use planning that could be addressed through the "Kesho" approach

Framework	Description	Application Examples	Gaps in Existing Framework
Dynamic Sustainability	The concept of dynamic sustainability was developed to support a pathways approach to managing sustainability challenges in a changing world. It is inclusive of dynamics, complexity, uncertainty and differing narratives by considering how aspects of stability, resilience, durability and robustness operate across temporal scales.	The dynamic sustainability framework has been used to conceptualise governance challenges associated with disease epidemics including using the examples of haemorrhagic fevers and avian influenza. The application aimed to develop sustainability pathways towards managing epidemics that moved beyond stability focused narratives by incorporating more nuanced aspects of resilience theory.	The framing enables researchers to evaluate sustainability in a changing world using concepts of both resilience and stability. Applications have so far not made tangible links with ecosystem service flows across spatial scales. Whilst applied in a theoretical sense to explore resilience focused pathways, it has not been linked with quantitative data to explore the implications of proposed trajectories of change.
Environmental Livelihood Security (ELS)	The ELS framework integrates sustainable livelihoods theory with water, energy and food nexus approaches. The approach was developed in response to a lack of consideration for livelihoods in nexus thinking. It aims to conceptualise the balance between human water energy and food needs with environmental sustainability.	The ESL framework has been used to investigate the environmental security of livelihoods in Southeast Asia and Oceania by assessing water, energy, food and livelihood interactions spatially using geospatial assessments. The framework was used specifically to explore the balance between natural supply and human demand for water, energy and food resources.	The ELS framework links social and ecological systems and considers the sustainability of these interactions on livelihoods using a water, energy, food nexus lens. Whilst spatial considerations are made, there is a lack of temporal consideration and therefore the evaluations are based more on stability than resilience over time. Moreover, though societal demand for water, energy and food resources plays a central role in nexus considerations, the mechanisms for community insights to be heard is not explicit.

Integrating principles from existing frames of thinking

To truly understand how change impacts people, it is useful to explore tangible evidence of environmental change with research on how resultant behaviours modify and shape outcomes. To achieve this, concepts from diverse research approaches can be combined and applied through participatory engagement. Here, two approaches to understanding sustainability are brought together to provide an integrated framework. Leach et al's (2010) dynamic sustainability framework is drawn upon to embed an understanding of how responses stimulate dynamic social-ecological relationships. Biggs et al's (2015) water-energy-food- livelihood framework is also included to explore what different responses to change mean for resource security, and ultimately the sustainability of livelihoods. This interplay between responses to change and water-energy-food security is explored specifically in relation to land use and land cover change and has the intention to help inform participatory scenario planning. Principles of the "*Kesho*" scenarios approach are therefore included (Capitani et al., 2018).

Integrative framework for exploring environmental sustainability of livelihoods

With consideration to previous insights, this article introduces an integrative framework for exploring the environmental sustainability of livelihoods. It incorporates a temporal scale (past, present, future) for analysing response strategies. By including a temporal dimension, the evolving nature of social-ecological relationships and longer-term changes can be better understood (Figure 4).

To assess the sustainability of people's responses to change, the framework aims to identify whether such responses are reactive or proactive. When reacting to a stress (long term changes) or shock (short-term perturbations) ex-post (after an environmental change) there can be an interval of increased vulnerability which pushes communities to exploit environments to try and meet their basic needs (Barbier et al., 2015). For example, drought can result in harvest failure, coastal communities may then intensify fishing activities to meet food security needs. Alternatively, proactive interventions might be undertaken; this could increase preparedness and decrease vulnerability. With foresight, a farmer may choose to invest in an irrigation system to overcome seasonal reductions in rainfall.

These styles of action (responsive and proactive) are positioned in the framework to show their relation to temporal aspects (short term shocks and longer-term changes). In this framing, long-term stresses are shown to depend on durability and resilience and lean towards proactive response strategies, whereas shocks rely on robustness within both systems and livelihoods and tend to result in responsive action to try and maintain stability.

All these interactions occur within a place; therefore, this framework attempts to explicitly connect them to land use or land cover changes. This is because land use and land cover change have a significant influence on the scale at which environmental challenges will be felt (Capitani et al., 2019).

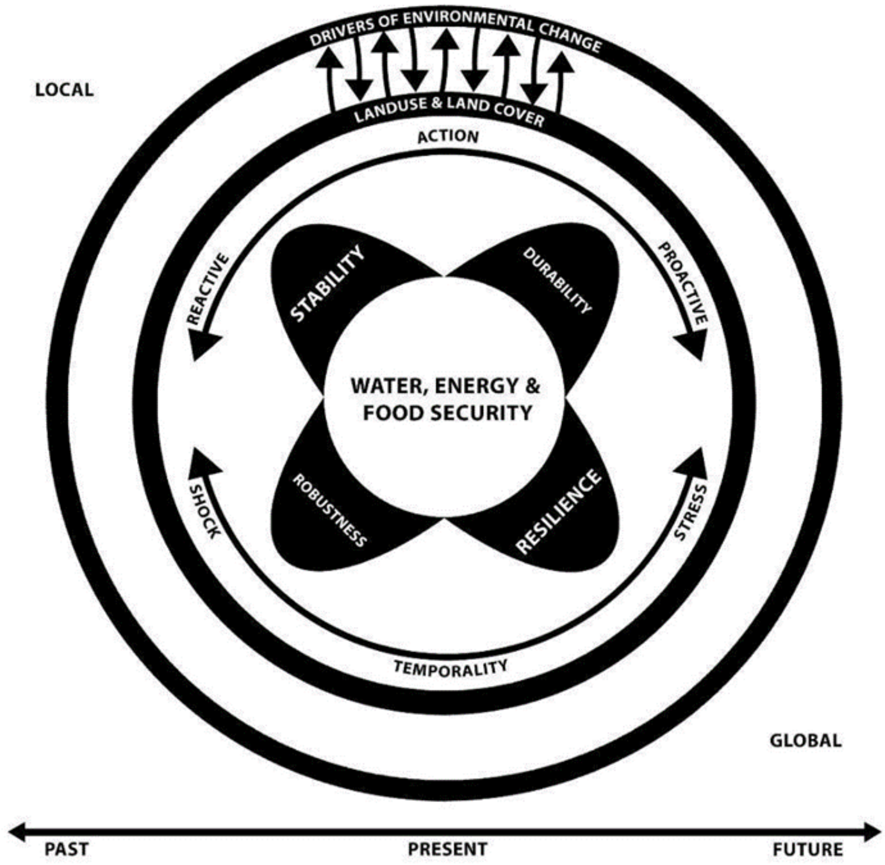

Figure 4. Environmental Sustainability of Livelihoods (ESL) framework for exploring how environmental drivers of change shape land use and how people's responses to such change shape the environmental sustainability of local livelihoods on small islands, drawing upon concepts from Biggs et al. (2014), Leach et al. (2010) and Capitani et al. (2018).

APPLICATION OF THE ESL CONCEPTUAL FRAMEWORK FOR ZANZIBAR

For the project in Zanzibar aspects of the ESL framework were applied across three stages of fieldwork. Focus groups with village elders and leaders were undertaken in Pemba and Unguja islands as part of a scoping study to learn about how people navigate their current environments to obtain water-energy-food security. Community-based workshops were then carried out to get a deeper understanding of how landscapes have changed and the implications of that on how people try to secure resources. The final stage brought this local knowledge into multi-stakeholder workshops and applied it to planning sustainability scenarios for the future (Table 2).

Table 2. Pathways approach for supporting the integration of local knowledge into problem framing and scenario development which supports sustainable land use and land cover management for effective water, energy and food security. This involves a three-step research approach (scoping, community-based workshops and multi-stakeholder scenarios workshops).

Research steps	**Aims**	**Practical application to Zanzibar case study**
Focus groups	Determine if and how socio-ecological relationships for resource use are evolving under environmental change through exploring adaptive responses.	Ten focus groups were undertaken with village leaders and elders (both males and females) in ten villages across Unguja and Pemba with a total of 40 participants. Sites represented diverse land cover types (peri-urban, coastal forest, mature forest farming and coastal). Focus groups used semi-structured interviews and were carried out in Swahili with the support of a translator. Each interview was recorded with a Dictaphone and lasted around two hours. The transcripts were then transcribed with the support of a Swahili and English speaking master's student.
Community workshops	Create a locally informed framework for scenarios development which frames challenges and opportunities for sustainability from a community perspective using a water-energy-food nexus lens	Community-based workshops were undertaken across the same ten sites (142 participants). Group size ranged from twelve to seventeen participants, were gender balanced and represented a range of age groups, from youth to elderly. In the workshops participants produced land use and land cover maps from twenty years ago to today. They identified changes and drivers of changes and evaluated impacts on water-energy-food security. They then made predictions about future changes and communicated ideas for solutions to emerging challenges. Workshops were 1 day each and conducted in Swahili with the support of a translator.
Multi-stakeholder scenarios workshops	Develop tangible scenarios alternatives to address actual and emerging challenges for water-energy-food security experienced by local communities in a small island context	Two one day scenario workshops were undertaken, one in Pemba (44 participants) and one in Unguja (23 participants). Stakeholders involved community representatives from all ten previous sites along with members from the following government sectors: agriculture, forestry, environment, water, energy and tourism. Two NGO bodies also contributed, these included: Milele foundation and Wildlife Conservation Society. In these workshops participants created timelines of land use and land cover change and evaluated impacts on WEF security. They then developed pathway narratives for supporting sustainable land use scenarios based on themes created by communities in earlier workshops. They predicted likely land use and land cover changes given each pathway alternative and finally reflected on the capacity of each framework to meet WEF needs. Workshops were conducted in Swahili again with the support of a translator.

DISCUSSION

Despite recent efforts to incorporate both social and environmental systems into conceptualisations of environmental sustainability, existing frameworks do not always adequately reflect local understandings of environmental sustainability and local knowledge about environmental change (Carter et al. 2014). There is some progress in rural adaptation, but this is still insufficient for the challenges that lie ahead; challenges that are particularly acute in coastal communities (IPBES, 2018). In many cases, social systems have been brought into conceptual discussions about environmental sustainability in ways that can overlook the knowledge of those most impacted by environmental change (Biggs et al., 2015). This is problematic given that local communities are typically highly dependent on natural resources to sustain their livelihoods (Mercer et al., 2014). Greater emphasis is needed to understand, and put in place, context specific sustainable land use plans that respond to the needs of those communities at the forefront of future adaptive challenges.

With this in mind, local knowledge and practice should be considered as the foundation for conversations on environmental sustainability and potential adaptation responses (Thorn, 2019). Whilst it is widely agreed that successful adaptation is contextually dependent, there is still a need for more studies which empirically explore how people perceive and respond to environmental change in specific cultural contexts (Tschakert et al., 2017; Thorn, 2019). As environmental change reshapes social-ecological relationships, more attention needs to be paid to the sustainability of response strategies adopted. To better support effective responses to change, there is a requirement for the integration of local community insights into research exploring effects of change and routes to adaptation.

The ESL framework presented in this article attempts to facilitate better understanding of how people respond to environmental change to meet their water-energy-food needs over temporal and spatial scales. In the development of the ESL framework attention was also paid to how local experiences could be better captured and integrated into local decision-making processes by applying its concepts to the *Kesho* scenarios approach. The *Kesho* approach uses participatory research methods to facilitate the integration of a range of knowledge (Capitani et al., 2019). In doing so, it can provide an opportunity to understand the environmental and social context and combine different expertise to assess the potential impacts of shocks and stresses (Kebede et al., 2018). Multiscale stakeholder engagement can be used in participatory processes to synthesise diverse knowledge in sustainability research (Tompkins et al., 2008; Mercer et al., 2012). Whilst previous scenario approaches towards sustainability have taken an environmental focus, this framework could be used to put local community needs at the centre of scenario planning.

CONCLUSION

Nexus thinking is needed to understand multiple types of change and their impacts for sustainable livelihoods in small islands, specifically due to the unique conditions they face (being geographically isolated, highly dependent on ecosystem services and facing rapid environmental change due to multiple drivers operating across a small area). This article introduces an integrative conceptual framework which links social-ecological and environmental sustainability ideas to explore livelihood outcomes under changing conditions in small islands. This framework emphasises the importance of exploring adaptation to rapid environmental change and how these responses reshape social-ecological interactions and ecosystem function and environmental livelihood security. As these interactions are forever changing, it is important to consider these relationships over appropriate temporal and spatial scales in an iterative approach. This framework can be used to integrate community perspectives into nexus approaches for tackling sustainability challenges. It has the potential to increase the agency of local communities within decision making processes and centralise poverty alleviation thinking into sustainable land use planning. Although the framework has been developed with specific considerations for sustainability challenges for small islands in the western Indian Ocean, it could be used in different contexts that experience constraints in terms of resources and which are highly threatened by global and local changes that are likely to become more challenging.

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2 SCOPING STUDY: A PEOPLE-CENTRED APPROACH FOR EXPLORING WATER, ENERGY AND FOOD SECURITY IN A SMALL DEVELOPING ISLAND

ABSTRACT

Small developing islands face several environmental and social pressures which impact resource security. This study uses a people-centred framework to investigate social- ecological interactions for water-energy-food security. Ten semi-structured focus group discussions were conducted in Pemba and Unguja islands with village elders and leaders. Results demonstrate that shocks and stresses affecting resource security are attributed to land use and resource competition, deforestation, climate change and insufficient resource infrastructure. The scale and strength of such pressures are heightened in dry seasons and correspond with spatial characteristics such as remoteness, intensity of land use and amount of natural resource capital. Whilst a number of adaptive responses are identified, these appear to be incremental and do not address the scale of the challenge. Maladaptive responses are also identified, most concerning is the use of poor quality water when piped water was disrupted, reduced nutritional intake during dry season and using unsustainable supplies or methods of obtaining fuelwood. Findings illustrate the importance of using people-centred approaches for understanding the complexity of social-ecological interactions for resource security. They also demonstrate that interventions for resource management need to consider spatial heterogeneity and temporality in terms of how specific land cover uses connect to differential pressures and adaptation capacity over time.

Key words: climate change, socio-ecological, land use competition, deforestation, resource management, adaptation, maladaptation

INTRODUCTION

Communities living in small developing islands face a number of emerging threats to livelihoods due to both environmental and climatic change (Poti et al., 2022). They are exposed to greater tropical and extratropical cyclone frequency and intensities, increasing air and sea surface temperatures, variable rainfall patterns and the associated impacts of sea level rise, such as swell waves, storm surges and sea water inundation (IPBES, 2018; Duvat et al., 2020; Mycoo et al, 2022). The effect of such threats on ecosystems is concerning given the strength of social-ecological interactions in small islands, which result from their relative isolation, and particular cultural identities associated with nature-based livelihoods (Nunn and Kumar, 2018). Alongside high exposure to the associated threats of environmental and climatic change, the adaptive capacity of communities living is small islands is also limited due to low-lying topography, scarce natural resources, isolation from major markets, dependence on external imports, competition for space, and associated socio-economic pressures (Nunn and Kumar, 2018; Douglass and Cooper, 2020). These conditions make communities and ecosystems in small islands especially vulnerable to rapid environmental change (Glaser et al., 2018; Cinner et al., 2018; Russell and Kueffer, 2019).

There are a number of studies which explore impacts of environmental and climate change on specific livelihood activities in small islands, such as agriculture, fishing or seaweed farming (i.e., Suckall et al., 2014; Makame et al., 2015; Brugere et al., 2020). However, there is less known about how environmental change influences the ways in which people meet their resource needs more broadly. This is surprising given that communities who live on small islands are especially dependent on ecosystem services to meet their basic needs of water, energy and food provision (Holding and Allen, 2015; Belmar et al., 2016; Astuti et al., 2019). There are a limited number of studies that investigate sustainability of systems in small islands more through a water, energy and food nexus lens (i.e., Chen et al., 2020; Borge-Diaz et al., 2021; Winters et al., 2022); more research is needed to understand how rapid environmental change affects water, energy and food security at the community scale (Biggs et al., 2014).

In order to understand how environmental pressures impact on people's everyday resource security, a research approach which focuses on people and their decision making is needed, recognising people as agents of change (Sen, 1980; Wise et al., 2014). Investigating how people respond to new resource pressures unveils how people can adjust and adapt to environmental change (Poti et al., 2022). By paying attention to the conditions in which responses occur, an understanding of levers and barriers to adaptive responses can be also generated (Duvat et al., 2020). Research exploring responses has previously shown that communities in small islands demonstrate an ability to respond to environmental change through collective action, supported by strong cultural identities and social connectedness (Glaser et al., 2018; Cinner et al., 2019).

Though communities have previously demonstrated great resilience under pressure, there is an urgent need to determine whether current responses are adequate in light of the scale of challenges faced, given the rapid nature of environmental change and the pressure this is placing on resources (Cinner et al., 2019; Mycoo et al., 2022). It is also important to learn how and why responses emerge across both temporal and spatial scales (Nunn and Kumar, 2017; Berthet et al., 2022). Such insights would facilitate greater awareness about changing social-ecological relationships and allow for feedback effects to be identified (Kurian, 2020). Harnessing this type of local knowledge requires effective input from local communities (Tschakert et al., 2017; Wilson & Forsyth, 2018; Lechuga Sánchez et al., 2021).

Whilst there is awareness that local knowledge is significant in terms of understanding the nature of adaptation, it is often neglected by policymakers and practitioners in sustainable land use and climate change adaptation planning (Holding and Allen, 2015; Hosen et al., 2020; Thorn et al., 2020; Parsons and Fisher, 2020). Overlooking local knowledge can result in failure to recognise emerging critical, autonomous, and incremental adaptations that may be most important to coping with environmental change, especially in the absence of formal planning (Thorn et al., 2015; Hagedoorn et al., 2019). When local-level adaptations are not drawn upon in policy planning, planned institutional adaptation can even end up being maladaptive by rebounding vulnerability, shifting vulnerability or compromising sustainable development (Juhola et al., 2016; Rahman and Hickey, 2019). Consequently, there is a need for national-level adaptation planning to be informed by locally derived adaptation processes (Fazey et al., 2010; Thorn et al., 2015).

This article attempts to contribute to the understanding of how local communities in small islands respond to rapid environmental changes to meet their water-energy-food needs using the case study sites of Unguja and Pemba. These sites form the two largest islands of the archipelago Zanzibar in the Western Indian Ocean, often underrepresented in environmental research (Poti et al., 2022). The aim of the study is to determine if and how socio-ecological relationships for resource use are evolving under environmental change through exploring adaptive responses. The key objectives are to: (1) identify key causes of change impacting on resource security; (2) determine whether adaptive responses enable communities to maintain or enhance resource security; and (3) identify any levers which influence adaptive responses to change. Results could be used to centralise local knowledge within planned adaptation processes in Zanzibar. They could also be used to inform how agendas such as the Zanzibar Vision for 2050, Sustainable Development Goals (SDGs) or African Agenda 2063 might address resource challenges in small islands more widely. This said, the study should be viewed as exploratory, providing initial insights which require further investigation.

CONCEPTUAL FRAMEWORK

This study attempts to evaluate how adaptive responses to environmental and climatic change contribute to water, energy and food security. A people-centred approach is applied to facilitate an understanding of how communities perceive environmental change and its impacts, and identify actions in response to such change. In doing so, communities are appropriately recognised as agents of change within social-ecological systems (Sen, 1980; Ayeb-Karlsson, 2016). The framework pays attention to spatial differences in how people respond to environmental change, where their adaptive response is temporary or ongoing, and the type of adaptive response they choose to make.

Much of the research in small islands focuses on vulnerabilities concentrated on coastlines due to intense resource pressures and exposure to seaward climate impacts (i.e., Dumaru, 2010; Ferrol-Schulte et al., 2013; Lange et al., 2015; Hagedoorn et al., 2019). However, there are other spatial indicators that might increase exposure to environmental change or people's capacity to adapt in small islands (Margles-Weis et al., 2016). These include factors such as: settlement and demographic patterns; lifestyles and economies; availability of natural resources; and environmental conditions (Duvat et al., 2017). Consequently, there is a need to capture how spatial heterogeneity across small islands might affect people's experiences of environmental change on resource security.

Analysis of the temporal dimensions of exposure and vulnerability to environmental change can also reveal how adaptive responses emerge and differ across different social groups (Duvat et al., 2017). Considering the temporality of responses from a community perspective is especially important, given that adaptation is a dynamic process, mediated by people's subjective experience of change (Frank et al., 2011). In this study, temporality of environmental changes is described in terms of shocks and stresses. Shocks are defined as perturbations which are temporarily bound and potentially recoverable, whereas stresses are considered to be ongoing pressures or perturbations which are experienced frequently (Leach et al., 2010).

To explore how social-ecological relationships evolve under shocks and stresses, there is a special focus on identifying adaptive responses. Here adaptation is defined as "the decision-making process and the set of actions undertaken to maintain the capacity to deal with future change or perturbations to a social-ecological system" (Nelson et al., 2007 p.397). Types of adaptive response are categorised into proactive or reactive responses. Proactive responses are considered to be pre-emptive to avoid declines in resource security, whereas reactive responses are implemented post shock or stress, often after an initial negative impact on resource security (Rahman and Hicky, 2019; Engler et al., 2021). Maladaptive responses are also recognised within the study. Maladaptation refers to less sustainable actions, which are implemented to cope in the short-term and counteract immediate negative impacts (Antwi-Agyei et al., 2014).

Any adaptive response to environmental change occurs within a context and, for this reason, levers and barriers are also considered in the framework. Here levers are defined as factors which determine the extent to which adaptive responses can occur (Wamsler et al., 2014). Barriers on the other hand are defined as constraining factors which limit adaptive capacity. An understanding of levers and barriers can offer an opportunity to modify conditions to enable more effective adaptation (Haasnoot et al., 2020).

STUDY AREA

Zanzibar (Figure 5) is a semi-autonomous territory, which has a political union with Tanzania but its own administrative government. The population growth rate was c. 3.1% in 2013 and is expected to fall to 2.8% by 2035 (OGS, 2018). The mean elevation is less than 20 m above sea level (Khamis et al., 2017). The islands have a humid tropical monsoon climate with 1600 - 1900 mm annual rainfall and an average annual temperature of 27.5°C (DoE, 2009). There are four main seasons, “kaskazi” (hot season) between December and February, “masika” (long rainy season) between March and May, “kipupwe” (cold season with high winds) between June and September, and “vuli” (short rains) between October and December – though climate variability has meant that seasonality is not as predicable anymore.

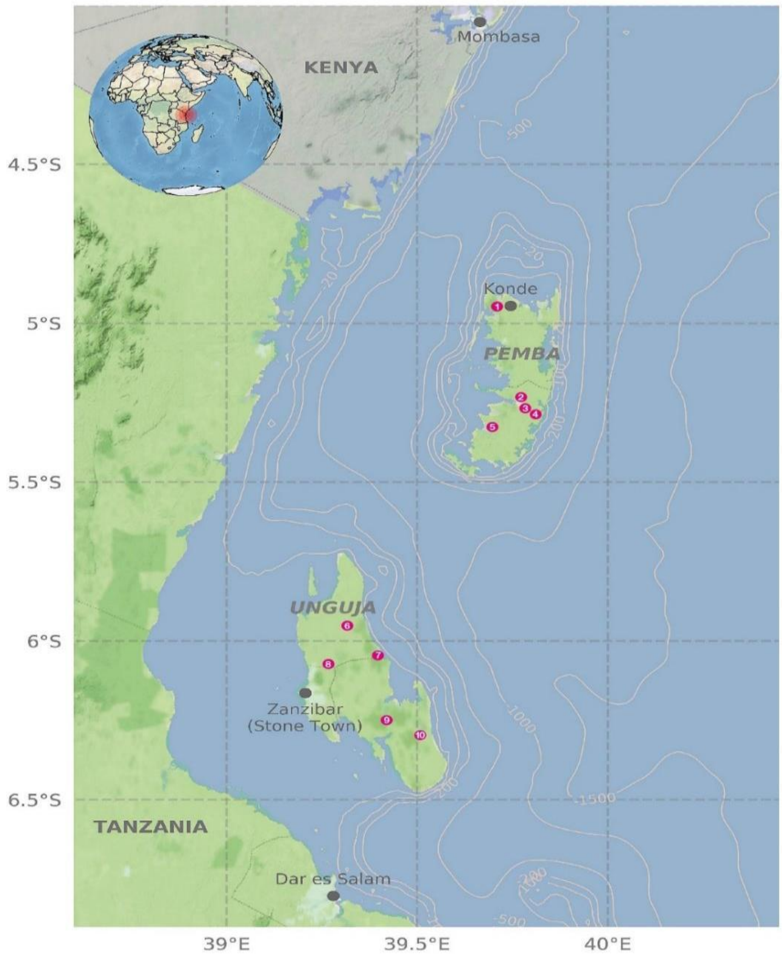

Figure 5. Location of Unguja and Pemba on the East African coastline, map provided by Leclair (2020). Sites in Unguja (left) and Pemba (right), coordinates provided by the Department of Renewable and Non-Renewable Resources, Zanzibar.

Most (approximately 95%) tourism occurs in Unguja, which contributes to 20% of the GDP. Historic lower rates of tourism in Pemba are due to limited transport, electricity and housing infrastructure and advertising (DCCFF, 2007). Today, coastal spaces are being altered by tourism infrastructure, associated water and waste management demands (Slade et al., 2012) and sand mining (Ladlow, 2015).

The majority of Zanzibar's residents are still heavily dependent on marine and terrestrial resources and resource based subsistence activities. Agriculture employs 42% of the population and contributes a quarter of the country's GDP (RGoZ, 2009). Important cash crops include coconut, mangoes, tomatoes, and cloves (Suckall et al., 2014; OCGS, 2015). Agroforestry, where trees and shrubs are grown in and around crops or pastureland, contributes to 2.8% of the GDP (OCGS, 2015). Conversely marine ecosystem services account for approximately 30% of the local GDP (Huge et al., 2018) including deep and shallow water fishing for octopus, squid, crabs, shrimps and mussels, seaweed farming and more recently sponge and pearl farming (Suckall at al., 2014) (see Figure 6).

Figure 6. Photos of land cover types in Unguja and Pemba, from top left to right including: mangrove forest Kisiwa Panza, Pemba; agroforestry Wambaa, Pemba; Ngezi forest reserve (moist forest), Pemba; Jambiani sandy beach, Unguja including beaches, seagrass meadows, algal beds and coral reefs; clove plantation Kizimbani, Unguja; farming and grassland area Pete, Unguja; small-scale farming Shamiani, Pemba; coral rag forest Pwani Mchangani, Unguja (by author).

Forest covers 28.9% of the land (Mwalusepo et al., 2017). Indigenous coral rag forests offer multiple benefits; they are an essential habitat for the Red Colobus monkey (endemic to Zanzibar) but are being overharvested for fuelwood needs (Nowak and Lee, 2011). They are also used for pegs and sticks for seaweed (Said and Misama, 2018). Protected forests include Jozani-Chwaka Bay, Kiwengwa-Pongwe forests and Ngezi. Coral rag forests are not fully acknowledged in terms of management and protection (Käykhö et al., 2011); whilst in some ward areas they might come under protection through community-based forest management plans (CoFMAS), they are not formally protected nationally.

As Zanzibar islands do not have permanent freshwater bodies, the population relies on rainwater aquifers to meet their needs. Differences in water density ensure that fresh groundwater floats on saline ocean water that permeates the porous geological substructure of the island, this results in the creation of freshwater lenses. The east coast of Unguja experiences the lowest levels of rainfall, elevated levels of transpiration and water demand pressures from the tourism industry, making it particularly susceptible to water scarcity (Gössling, 2001). Zanzibar's water authority (ZAWA) abstracts water from caves to supply several communities with water via untreated pipelines. Villages on the east coast are largely supplied by pipelines connected to sources further inland. Not all villages are connected to a pipeline; some rely on locally constructed wells or caves (Gössling, 2001).

Zanzibar's electricity supply is provided through a submarine cable from mainland Tanzania. Rural villages began being connected to the national grid in the 1980's. However, the uptake is relatively low as it costs the average household 4-6 months' worth of income to establish the connection.

METHODS

Site selection

Ten focus group discussions were conducted covering thirteen "Shehia" areas (wards) across Unguja (n=16) and Pemba (n=24) between April and August 2019. Within these sites protected forest spaces, coral rag forests, peri urban areas, commercial farming and plantation areas, small scale farming, agroforestry and coastal areas were all represented to ensure inclusivity across land cover types (Table 3).

Table 3. Focus group locations and attendance of participants. In Shehia areas where there had been subdivisions in the last 20 years, both areas were included due to the temporal scope of the study. Sites were selected to represent a range of land cover types; the main reason for the selection is highlighted in bold. All sites had areas of small-scale farming. Participants included women (n = 17) and men (n = 23).

Focus group location	***Shehia* (village) areas included**	**Main land cover type represented**	**Participants included**
Macho Mane	Macho Mane and Mkoroshoni	Peri urban	Two *Shehas (village leaders)* (men: 2) and four village elders (men: 2, women: 2)
Mfikiwa	Mfikiwa	Commercial farming	One *Sheha* (women:1) and two village elders (men: 1, women: 1)
Pujini	Pujini and Dodo	Commercial farming and mangrove cover	Two *Shehas* (men: 2) and four village elders (men: 2, women: 2)
Chumbageni	Chumbageni and Wambaa	Coastal with some tourism	Two *Shehas* (men: 2) and four village elders (men: 2, women: 2)
Mji Mpya	Mji Mpya	Protected forest	One *Sheha* (men: 1) and two villages' elders (men: 1, women: 1)
Jambiani Kikadini	Jambiani Kikadini	Coastal with high levels of tourism	One *Sheha* (men: 1) two village elders (men: 1, women: 1)
Pongwe	Pongwe	Coastal with medium levels of tourism and some mangrove cover	Three elders (men: 1, women: 2)
Kinyasini	Kinyasini	Peri urban and commercial farming	One *Sheha* (men: 1) and two village elders (men: 1, women: 1)
Kizimbani	Kizimbani	Commercial farming (in particular spice farming)	One *Sheha* (women: 1) and three village elders (men: 2, women: 1)

Participant selection for focus groups

Village leaders and elders were selected for the focus group interview because: (1) they are respected individuals in the community, maintaining and shaping the social values (Dean, 2013); (2) they have a long term overview of social, cultural and environmental change with a rooted sense of place (Mustelin et al., 2010); and (3) they have important roles in knowledge construction at the family level, and broader social transformation (Holmes, 2002). In Zanzibar, engaging with village leaders and elders in the first instance is also the respected protocol and is important for building longer-term community relationships.

Local regulations were followed in terms of engaging the “Sheha” (village leader) to gain permission to conduct the research, select participants and discuss the research agenda. As the project was supervised by the Department of Forestry and Renewable and Non-renewable Resources in Zanzibar, a representative from this government department made contact with the village leaders, village leaders then engaged village elders. Village leaders were asked to select at least one woman and one man to be part of the discussion.

Focus group framing

The first author spent nine months living and working in rural, urban and peri-urban sites in Unguja and Pemba: from April to September 2018, based in Stonetown and Pwani Mchangani, and then from February to April 2019 based in Pwani Mchangani and Macho Mane. This period encompassed the “masika'' rainy season to observe seasonal variability in livelihood activities. During this time, the lead author was embedded in the day-to-day activities of community members. Observations were made around local people’s perceptions about the causes of environmental change and their impacts on water, energy and food security. These observations then informed the objectives of the study and themes of the focus group discussions.

Focus group discussions

Focus group discussions were used because the dynamic of a group discussion stimulates memories of historical changes and gives space for different perspectives regarding events (Kitzinger, 1995), therefore allowing for a robust synthesis of social-ecological changes to be developed. The core themes in the focus group discussions included: social context, demographic changes, responses to changes in resource security and visions for the future. Questions of change were temporally bound to the preceding twenty years because this was a period in which respondents could relate to in terms of their personal memory. Interviews were conducted in Swahili, with the support of a translator, at the homes of village leaders or in communal halls. They lasted approximately two hours and were recorded with a dictaphone. Participants were informed of their rights, including consent, anonymity, and voluntary participation. Participants were remunerated for their time as is common across Tanzania.

As the village leader’s role is often to communicate on behalf of the community, or disseminate information to the community, there was a risk that their status could result in a dominance effect (where one person mainly contributes to the discussion) or a halo effect (where the status of one person influences the discussion) (Nyumba et al., 2018). To facilitate a more balanced discussion questions were directed at different individuals within the group at various points of the discussion. The facilitator was also encouraged to draw out discussion from quieter participants (see Appendix 1.1).

Analysis

Notes were taken during the focus group discussions and were analysed together with the transcripts to connect specific details with contextual elements and thus offer a more integrative and holistic understanding (Hamo et al., 2004). Data was analysed in NVivo 12 Pro and systematically coded using a cross-sectional coding and retrieval method (Spencer et al., 2003). Shocks and stresses were delineated to demonstrate their perceived causes. Adaptations were organised into four main themes, proactive, reactive, autonomous or maladaptive. Labels were added to identify whether different islands demonstrated different themes. Key illustrative quotes were used to demonstrate how environmental and socio-economic changes had altered resource security alongside adaptation strategies.

RESULTS

Identified shocks and stresses

Results from the focus group discussions revealed a number of shocks and stresses which impact resource security. Shocks included crop pests and diseases, disruptions in piped water supply, flooding from rainfall events and infrequent sea water inundation (i.e., seemingly a one-off event). Stresses included frequent harvest losses attributed to climate change, frequent sea water inundation, depletion of fuelwood sources, reduced space for farming and soils and reductions in soil fertility. Whilst this research focused on terrestrial landscapes, participants also raised concerns over sea temperature increase and the lowering of fish stocks and seaweed farming yields in coastal areas. Shocks and stresses were thought to be caused by land use competition, deforestation and forest degradation, climate change and inadequate service infrastructure (Figure 7).

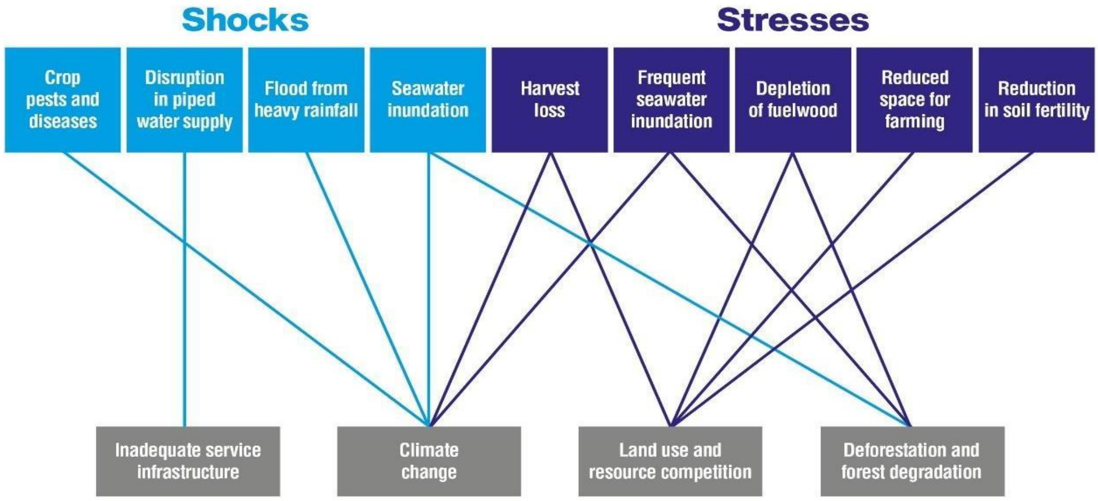

Figure 7. Shocks and stresses categorised into key factors driving associated shocks and stresses according to connections identified in focus groups. Three of the categories demonstrate multiple linkages and are selected as the main focus for drivers of change in this study.

Land cover types associated with a higher prevalence of shocks and stresses included coastal areas, especially areas with degraded mangrove forest cover. This was thought to be because as well as facing more generalised pressures, coastal areas also faced specific pressures associated with sea level rise, seawater inundation, salinization of groundwater supplies and in some cases land use competition associated with tourism. In Unguja specifically, a large number of stresses were also found in the area adjacent to a protected forest. This was partly because it is also adjacent to a large mangrove forest and experiences sea water inundation. Key differences between islands included a higher prevalence of soil infertility due to the increased farming intensity mentioned in Pemba than Unguja and saltwater intrusion of groundwater occurring only in the sites surveyed in Unguja (Table 4).

Table 4. Shocks and stresses occurring over different land cover types in Pemba (P) and Unguja (U).

	Peri urban		**Coastal**		**Protected forest**		**Commercial farming**	
	P	*U*	*P*	*U*	*P*	*U*	*P*	*U*
Crop pests and diseases		■						■
Disruption of piped water supply	■		■	■	■	■	■	■
Flood from heavy rainfall			■					
Seawater inundation			■					
Harvest loss	■	■	■	■	■	■	■	■
Frequent sea water inundation				■		■		
Depletion of fuelwood	■	■	■	■		■	■	■
Reduced space for farming		■	■	■		■	■	
Reduction in soil fertility	■			■	■		■	
Total	*4*	*4*	*6*	*6*	*3*	*5*	*5*	*4*

Impacts on resource security

Inadequate service infrastructure

Inadequate service infrastructure was described as a challenge for water and energy security, despite improvements in the provision of electricity and piped water across both islands. Whilst some villages had access to a continuous supply of piped water, others were yet to have a connection at all and had to buy water supplies using transport, travel to collect piped water or use lower quality well water. Well-connected villages still face perturbations when pipes need repair or electric pumps cannot function, though this is described as infrequent.

Despite the frequency of power cuts that occur across Zanzibar, it was only mentioned as a minor issue in one focus group. This was possibly because electricity use was often limited to phone charging and lighting. Greater utilisation of electricity was in many cases not achievable due to the lack of financial capacity to invest in appliances such as fridges and ovens, fuelwood remains the primary source of energy. Few households used solar panels for charging phones and lighting.

Climate change

Climate change presented another major cause of challenges for resource security. Across all study sites participants agreed that climate has altered over the last twenty years, as detailed by a participant in Pemba’s peri-urban area:

> *“The climate has really changed in the last twenty years. Now in the dry season the sun is very hot and in the rainy season the water is not as strong as before. Twenty years ago, the rain would be strong and could continue over several days, but today it lasts a few minutes and stops.”* (Macho Mane and Mkoroshoni, April 2019)

Lack of rainfall was thought to have caused reductions in crop yields through drying of the crops as well as increased risk of pests and diseases. It was also thought to have impacted the health of cows due to the resultant lack of fodder. The unpredictability of rainfall was also found to be an issue, as when it falls out of season standing water can increase the risk of disease and cause rotting of ground crops, such as cassava and sweet potato.

Sea level rise and wave over wash, attributed in part to climate change, caused problems for both water and food security. In Wambaa, a coastal area of Pemba, sea water inundation led to salinization of agricultural land, impacting local food security.

Land use and resource competition

Settlement expansion, arising from population growth, the continued practice of subdivision of plots across generations and coastal squeeze from tourism, reduced the availability of agricultural land for smallholder farming plots, predominately in Unguja (see Table 5). Limited agricultural land resulted in continuous farming with no fallow periods or crop rotation. A participant in Jambiani Kikadini outlined the impact of this on food security:

> *"The majority are now buying [food] whereas before they would normally produce more foods and buy only a few. The changes are because of population increase, the area to farm is reduced."* (Jambiani Kikadini, July 2019)

Some participants perceived that land scarcity also contributed to a decrease in soil fertility due to the resultant intensification of farming. In the peri-urban area of Pemba and coastal area of Unguja participants discussed increasing the use of chemicals (e.g., fertiliser, pesticide and insecticide):

> *"Right now, [...] the soil fertility has declined, so if you don't put the fertiliser or you don't put the insecticide, you will get nothing or low product."* (Pongwe, July 2019)

This said, farming inputs could also be connected to the transition from smallholder subsistence (e.g., cassava, sweet potato, bananas) to commercial high value cash crops (e.g., tomatoes, cabbages, watermelon).

In addition to challenges related to crop production, land use competition contributed to conflicts between farmers and pastoralists as livestock encroached into cultivated areas, this was observed in Pete, Unguja.

Alongside challenges related to land scarcity, were issues of increased demand for resources. In Pete, the Sheha explained that:

"The price [of food] has increased because of the demand from tourism means that the communities are not supplied" (Pete, July 2019)

This was thought to be especially the case in high seasons for tourism, which coincide with dry seasons, causing an exacerbation in food security.

One village elder in Pemba also commented on how the capacity of people to share resources have declined, compromising reciprocity:

"Before you didn't have to ask permission to collect dry clove wood you could just go and get it. But now you must go to the owner and get permission and he might say no because he needs it himself" (Chumbageni and Wambaa, April 2019)

This points to a general decline in resource availability, which may affect the traditional social dynamics within this small island context.

Table 5. The distribution of (1) identified changes to climate; (2) types of deforestation and (3) causes of land use competition, and (4) issues with service infrastructure—across key land cover types and islands.

		Peri urban		**Coastal**		**Protected forest**		**Commercial farming**	
		P	*U*	*P*	*U*	*P*	*U*	*P*	*U*
1	Hotter dry season	■			■		■	■	
	Less rain in rainy season	■			■			■	■
	Longer dry season				■				■
	Changes to sea level or temperature			■	■		■		
	Unexpected rainfall		■	■		■			■
2	Community forest	■	■	■	■	■	■	■	■
	Mature forests				■		■	■	
	Commercial forest			■			■		
	Mangrove			■	■				
3	Settlement expansion	■	■		■		■		
	Coastal squeeze				■				
4	Perturbations in piped water supply	■	■	■	■	■	■	■	■
	Inadequate piped water supply	■				■		■	
	No access to electricity					■			
	Total	*6*	*4*	*6*	*10*	*5*	*7*	*6*	*5*

Deforestation and forest degradation

Deforestation and forest degradation was raised as a concern across all sites. Due to extreme overharvesting of coral rag forests, evidence from inland and coastal areas across both islands suggests commercial forests (including clove and mango) were being harvested for fuelwood. In some coastal areas mangrove forests were also being used for fuelwood and timber in the construction of houses.

Agricultural expansion was another cause of deforestation, outlined in a focus group based in a commercial farming area in Pemba:

> *"The forest in Mfikiwa has been gone since 2000 because we needed more space for farming, and we cut it for building and for making charcoal […] we lost the forest very fast because we had the chainsaw."* (Mfikiwa, April 2019)

In Unguja, anxiety around land acquisition for the gazettement of the protected forest was communicated as a major driver in rapid deforestation:

> *"There was a huge amount of forest loss 12 years ago, where one big area was cleared. This was because in 2004 the national park policy came into effect and they needed a big area to meet the conditions, so they took a large area of Pete village. The community felt that the remaining forest would be taken by the national park, so we cut the trees and planted crops instead, as they would not want the empty land."* (Pete, July 2019)

Deforestation has had multiple implications for livelihoods. Mangrove deforestation and degradation was thought to be the main cause for seawater inundation into coastal villages. In Wambaa, Pemba, deforestation of mangrove contributed to coastal inundation and the salinisation of agricultural soil.

Communities in Kinyasini, Kizimbani and Pongwe specifically made the association between deforestation and reductions in groundwater levels, as seen in lower water levels in village wells:

> *"Water is reduced because the forest attracts rain. In the past, there was much [more] water in the rivers. [There was] even [water in the rivers] in summer, because the forest was thick, but now there is a shortage of water."* (Kinyasini, July 2019)

In Mji Mpya, adjacent to Ngezi forest reserve in Pemba, the community also described a relationship between forest and rainfall:

> *"We get a good amount of rain because the forest is breathing well to get rain, it's also cooler here because the forest keeps things cool"* (Mji Mpya, April 2019)

Insights into the benefits of forests for water security appeared to give communities greater motivation for protecting forest spaces.

Responses to shocks and stresses

Responses to shocks

Adaptation to shocks affecting resource security was limited, but there were two examples, both reactive. After two heavy rainfall events, evidence from the coastal site in Pemba demonstrated community cohesion as the community, with support from the government, worked together to repair damage and recover. Similarly, after a seawater inundation event in the same area, the community lobbied for a seawall to protect agricultural plots, thereby attempting to tackle the cause of the shock and enhance robustness through preventing further inundation events (see Table 6). However, participants commented that they still experienced inundation, as the seawall just redirected the water. So, whilst the agricultural area was protected, there were still some ongoing concerns.

Table 6. Responses to shocks and stresses (1) positive adaptations in response to shocks and stresses and (2) maladaptive responses to shocks and stresses.

		Peri urban		**Coastal**		**Protected forest**		**Commercial farming**	
		P	*U*	*P*	*U*	*P*	*U*	*P*	*U*
1	Collaborative recovery after flood			■					
	Construction of sea defences			■	■		■		
	Improvement of water infrastructure	■	■	■	■	■	■	■	■
	Improvement of electricity infrastructure	■	■	■	■		■	■	■
	Benefit sharing from ecotourism						■		
	Relocation landwards				■				
	Establishment of woodlots		■		■				
	Alternative livelihood	■	■	■		■	■	■	■
	Migration			■		■		■	
2	Reverting to well water use	■		■		■	■	■	
	Using poor quality fuelwood							■	■
	Travelling further for fuelwood				■	■	■	■	
	Using unsustainable fuelwood			■			■		
	Buying fuelwood	■	■			■			
	Decreasing nutritional intake	■	■					■	
	Relying on food imports		■	■					■
	Intensification of agriculture	■			■				

Responses to stresses

There were a greater number of examples identified for reacting to stresses. For example, in response to perceived sea level rise, the community in the coastal area with high levels of tourism in Unguja demonstrated a trend of proactively relocating their household plots landward. This coincided with the selling of beach plots for tourism - allowing people to resettle and have funds to build the “modern house” using blocks and corrugated iron sheet roofing in place of coral rocks and dried coconut leaves or grass. In reaction to sea water inundation, one community planted trees along the coastline. Similarly, another planted mangroves and filled some areas with gravel to try and redirect water away from the village.

In both coastal and peri-urban areas in Unguja communities were proactively establishing woodlots for personal and or commercial provision in response to fuelwood depletion, often in place of food crops. Also, in attempting to cope with instances of drought, some farmers were proactively implementing irrigation systems connected to individually dug boreholes – though this was thought to be very limited.

More broadly, in response to ongoing stresses, there was a reactive transition away from subsistence-based livelihoods to income generating roles. This was described as partly due to the unsustainability of traditional roles, as described by an elder in Pemba:

> *“A lot of people who used to do farming have had to find alternative work. This is because there is a lack of fertility in the soil, before you could have a small plot and grow a lot but now even if you have a big plot, you can only harvest a little”* (Macho Mane and Mkoroshoni, April 2019)

Alongside a lack of interest to continue with subsistence-based livelihoods:

> *“There is more education of people but there is a loss of culture to do cultivation and traditional livelihoods because people feel too proud”* (Chumbageni and Wambaa, April 2019)

As a result, there was an increase in the movement of people to urban areas, coastal areas or areas with greater natural capital. Coastal areas offered more informal and formal employment opportunities relating to tourism and attracted seasonal fishers, urban centres attracted vendors and areas with natural capital appealed to farmers and pastoralists.

Maladaptive responses

A number of maladaptive responses to resource insecurity were also identified. For example, evidence from Pemba and Unguja demonstrated that when piped water supply is insufficient or disrupted, people revert to well water (especially during the rainy season), which is of lower quality, therefore increasing their risk to waterborne diseases. Communities from all sites also stated that some members of the community still use well water, it is unclear why, but the 4000

Tsh per month cost to Zanzibar's Water Authority (ZAWA) for piped water could be a potential factor. Whilst it is advised by the health authority that well water should be treated by boiling, it is acknowledged by participants in Pemba that in most cases people do not do this. As the piped water supply is deemed reliable, communities are sometimes not maintaining the quality of well water through treatment (communities refer to treating with calcium or 'water guard'), so when faced with a disruption in supply, the quality of the water they revert to is poor.

Maladaptive responses were also identified with regards to maintaining fuelwood supplies. The reduction in availability and access of fuelwood resulted in communities across coastal regions, areas with high levels of commercial farming and even adjacent to protected forests, travelling further to collect fuelwood; sometimes into other villages boundaries where there are remaining forest stands. Distance travelled to collect fuelwood could go up to 5km from their households. This increased the time budget for collection of fuelwoods, a task found to be mostly undertaken by women and girls. Some people in peri-urban communities transitioned to buying fuelwood. However, in peri-urban areas and commercial farming areas some households reverted to using lower quality fuelwood, such as dried coconut palm, sawdust, or thinner sticks. Moreover, as outlined above, in areas where community utilisation forest (coral rag) is depleted, communities sometimes used plantation forest or protected mangrove forests to meet energy needs; this is counterproductive as plantation yields could be reduced and coastal defences weakened.

Communities further described maladaptive strategies for coping with food insecurity when food production in household farms is low, which is particularly pertinent in the dry season. Communities often reacted by rationing their food supply or changing their diet. This meant that households limited their food intake by eating less meals a day, having a smaller portion size or eating a higher proportion of carbohydrate to compensate for lack of protein and vegetables. In one village in Pemba, elders explained that this had implications for the health of children, resulting in a swollen stomach from severe malnutrition. As a result of gradually declining harvests due to reduced soil fertility and space for farming, communities also indicated a growing reliance of bought food items:

> *"Before there was enough food and people were farming for themselves, but now people are depending on the shops because the crops in the farm are few."* (Pongwe, July 2019)

Challenges around food price inflation for imported foodstuffs (especially rice) were raised in nine of the ten sites interviewed. Also, because income generating opportunities were often insecure, the instability of income causes fluctuations in food security, as stated by an elder in Pemba:

> *"It's also hard sometimes because the price of food is high and the process of getting money difficult"* (Chumbageni and Wambaa, April 2019)

The combination of pressures influencing food security point towards more precarious mechanisms for obtaining adequate nutrition, relying on a mixed approach of subsistence farming and buying food, consequently communities experienced greater exposure to multiple pressures as a result.

Levers and barriers

Levers and barriers to adaptation were linked to the landscape. Spatial aspects such as remoteness, resource demand and natural capital resulted in variations in exposure to shocks and stresses and influenced adaptive capacity (Table 7). Some social characteristics also shaped levers and barriers. Financial capacity determined whether households could implement irrigation, electricity, solar panels or extension of water pipelines to homes. Education influenced people's adaptive potential with regards to accessing alternative livelihoods. Enhanced literacy meant that some people were able to move away from subsistence-based livelihoods and into paid employment. This said there were barriers which also impeded this transition, a lack of language and education relating to tourism prevented many from accessing well paid positions in the tourism sector, which is a major employer in Zanzibar. Individuals from local communities were often limited to lower paid positions in roles such as gardening, housekeeping and security.

Table 7. Spatial considerations relating causes of shocks and stresses alongside the villages where they were identified.

Spatial feature	Consequence of spatial feature	Villages identified
Remoteness	Inaccessibility of electricity	Mji Mpya
High levels of commercial farming	Increased land use competition and resultant deforestation	Mfikiwa, Pujini, Dodo, Kinyasini
Urbanisation	Increased land use competition and resultant deforestation as well as pollution concerns	Macho Mane, Mkoroshoni
Coastal areas populated with mangroves	Risk of sea water inundation and salinization of groundwater	Pujini, Dodo, Wambaa, Pete
Areas with standing forest reserves	Producing charcoal for supplying other villages, resulting in increased pressures on forests	Jambiani Kikadini, Mji Mpya
High levels of natural capital	Shared benefits from ecotourism - which supported the digging of a borehole and installation of a water pump to generate tap water	Pete
Coastal areas popular with tourism	High value of coastal plots to sell or rent	Jambiani Kikadini

Discussion

Although social dynamics have been identified as critical to understanding resource security, there has been insufficient understanding about social and cultural contexts within research exploring water, energy and food systems (Albrecht et al., 2018). This is in part due to the lack of qualitative methods (Foran, 2015; Albrecht et al., 2018). The findings of this study contribute to wider research which recognises the importance of local knowledge for understanding responses to water, energy and food challenges, and how these operate according to spatial characteristics over varying temporal scales (Biggs et al., 2014; Shultz et al., 2016; Albrecht et al., 2018). In doing so, this study provides an example of how qualitative methods can be used to gain insights into social-ecological relationships affecting water, energy and food resources.

Findings demonstrate that shocks and stresses affecting resource security are spatially heterogeneous across land cover types in small islands. Four main factors influence the intensity of shocks and stresses, these include: exposure to climate threats; land use intensity; quality of natural capital and remoteness. Key areas for vulnerability to resource pressures included places with intense land use pressures and those with close proximity to the sea. However, findings also suggest that consideration needs to be given to how vulnerabilities in one area might contribute to pressures in less vulnerable areas with high levels of natural capital.

For instance, results here indicate that as forests are depleted in one village, pressure mounts in spaces with comparatively more forest through increased extraction of fuelwood. Evidence from wider literature has also shown that as new sites get connected with piped water, existing connections experience reduced supply (Gössling, 2001; Makeme & Kangalawe, 2018). If these effects are not pre-empted and sustainably managed, then vulnerability is likely to shift or spread into new areas (Duvat et al., 2017). Considering how feedback effects of social-ecological issues might operate over extended spatial areas, land use management needs to be viewed at the landscape scale, whilst also taking into account place-specific complexities (Schultz et al., 2016).

Shocks and stresses also vary temporally. Water insecurities are exacerbated in the dry season due to inadequate rainfall and high temperatures, which impacts crop growth and freshwater recharge of aquifers (Gössling, 2001). Dry season coincides with increased resource demand from tourism. For instance, Makame et al (2015) found that competition for seafood means that communities can often only obtain smaller fish such as anchovies, as larger catch is sold to hotels. Water challenges on the east coast of Unguja island are also intensified during the high tourism season. Communities in villages on the east coast already receive comparatively less rainfall and higher rates of evapotranspiration. This is then layered with extreme rates of over extraction (Slade, 2012). Over extraction, alongside increased temperature and decreased rainfall, has contributed to salination of water wells. Makame & Kangalawe (2018) found that in some areas of Zanzibar communities have no other option than to cook with and drink salinized water due to the lack of alternatives.

Temporality also influences adaptive response types, with responses to shocks being reactive and responses to stresses often more proactive. Robert et al (2016) explain that proactive responses are associated with adaptive capacity over time, whereas reactive responses occur instantaneously, meaning that communities adapt without any anticipation. This suggests that reactive behaviour stems from low access to information, which potentially means higher exposure to vulnerability because of a subsequent inability to plan adaptation (Andersson et al., 2020; Engler et al., 2021). This said, knowledge about stresses in the study appeared to derive from subjective experience and personal histories, which indicates that before the onset of a 'stress', information may not have been available either. Consequently, there may be differences in responses across the temporal scale of a stress also. Reactive responses in this study were linked to flooding, one because of heavy rainfall and the other sea water inundation. Communities might therefore benefit from early weather warnings (Nhamo et al., 2019; Andersson et al., 2020). However, this needs to be coupled with appropriate planned adaptation strategies to implement upon hearing such warnings.

As is the case in many small islands, effective community-based adaptation appears to be limited, and does not address the scale of the challenges they face entirely (Mycoo et al., 2022). Attention should therefore be paid to some of the levers which appeared to facilitate adaptive responses (Dumara, 2010; Mersha and Laerhoven, 2018). In line with existing research, social connectedness is found to enhance the adaptive capacity of communities (Petzold and Ratter, 2015; Nunn and Kumar, 2018). This was especially the case when responding reactively to shocks experienced at the community level. However, findings also suggest that a reduction in resource availability reduces reciprocity, and that there is an increase in the movement of people, in part because of the unsustainability of livelihoods. The effects of resource scarcity and increased movement of people on social connectedness, alongside implications for adaptive capacity are still not well understood and need further investigation.

A number of other levers are found to enhance people's capacity to respond more proactively. Land ownership, especially in tourism hotspots, appears to serve as a currency for responding to change. However, Huruma (2014) found that in selling land people in Zanzibar jeopardised their livelihoods through decreased access to beaches, reduced family assets for the future, and increased resource competition. They suggest that the government needs to guide local people on how to manage their land assets through joint ventures, which are mutually favourable. Rather than selling land, Scheyvens and Hughes (2019) recommend leasing of land under robust policy frameworks to ensure more long-term benefit sharing from tourism. More research is needed to explore the conditions in which people decide to sell or lease land, alongside the short-term and long-term implications of doing so.

Education is found to enhance people's mobility, meaning when 'traditional' livelihoods become unsustainable they have some capacity to transition into income generating roles. Poti et al (2022) found that climate induced migration occurs within communities across the Western Indian Ocean. Wider research has shown that the likelihood of migrating due to the instability of livelihoods caused by climate change increases with educational status (Bohra-Mishra et al., 2017). Within Zanzibar participants in rural villages explained that men migrate in search of work, internally (often from Pemba to Unguja), but also externally to countries such as Dubai and Europe. Further research is needed to better understand the conditions that support migration and whether it actually leads to more sustainable livelihoods. Research into the experience of women in the community when men travel in search of work is also needed, especially given that they often remain in the village setting. Questions might explore livelihood security temporally, for instance, is there an initial increased level of vulnerability in the household when one person leaves in search for employment?

Financial capital further determines whether people can invest in more sustainable practices, such as irrigation, the establishment of woodlots or installation of solar panels. Participants often explained that whilst these activities were deemed effective, that they were limited to the few who had financial capital. Considering the strength of social capital in small islands (Petzold and Ratter, 2015), it might be useful to think about how these activities could be implemented as a group rather than individually. This might lend itself with the engagement of supportive institutions and routes to access microfinance. Robinson (2020) proposed that climate finance needs to focus on locally appropriate adaptation, given that planned structural adaptation, such as seawalls, have often been ineffective. This might involve exploring the suitability criteria and barriers to uptake for these identified adaptations, alongside possible funding streams to support implementation and management.

Worryingly, findings suggest that maladaptive responses are common in Zanzibar. Whether an action is adaptive or maladaptive depends on the social-ecological context, which can change over space and time (Wise et al., 2014). Even actions which address a shock or stress in the short-term can often fail to address the underlying causes of vulnerability, leading to maladaptation over time (Kelman, 2014). Poti et al (2022) state that planned adaptation in small islands appears to be most effective when co-managed with stakeholders, due to the complex network of actors at play. Co-designing planned adaptation could help to address barriers, associated with resources, regulations, governance and learning, which have impacted adaptive capacity in the past (Suckall et al., 2014; Mycoo et al., 2022). It could also help to integrate incremental adaptation on proximate causes with more transformative action (Wise et al., 2014; Poti et al., 2022).

Interconnections between water, energy and food outcomes for adaptive responses were also revealed. In many small islands there is a general lack of long-term planning for adaptive management strategies which respond to nexus challenges (Ding et al., 2019; Mycoo et al., 2022; Winters et al., 2022). Existing data also often fails to incorporate seasonal differences in shocks and stresses and their impacts across the nexus (Stylianopoulou et al., 2020; Winters et al., 2022). These findings show connections such as: the need for electricity to operate water pumps; the link between deforestation for energy and groundwater supply; and the association between ground water supply and food production. In doing so, results reveal water security as a cross cutting issue across the nexus, and possibly an effective entry point for exploring sustainability issues more broadly. They also help to point out interactions between identified causes of shocks and stresses and the implications these have across the water, food and energy nexus. These include land use competition contributing to challenges in fuelwood supply and space for agriculture, and climate change impacting water availability and food production. Monitoring of emerging imbalances in the water, energy and food nexus should be central to informing adaptive management, especially in small islands where social-ecological interconnections are so tight (Winters et al., 2022).

LIMITATIONS

Future research would benefit from greater input from other social groups, such as youth, as elders often have a role in maintaining traditional cultural identities, and therefore may not portray alternative perceptions. There is also a possibility that more contentious issues might not have been raised considering that: (1) the position the participants made meant they could not be anonymous and (2) the discussions had to be supervised by a member from a government department according to local protocol at the time. To unveil potential political issues affecting resource security, methods which allow for complete anonymity are needed; this might involve one-to-one interviews. Finally, by sampling through gatekeepers, who have a position of power in the community, there is a chance that people who share a similar viewpoint are selected. Future research might try to adopt a more random approach to sampling to overcome this.

CONCLUSION

This study contributes to the understanding of how social-ecological relationships for resource use are changing according to people's experience of rapid environmental change. Findings reveal that inadequate service infrastructure, land use intensity, climate change and deforestation result in shocks and stresses affecting resources. The most frequently mentioned impacts relate to harvest loss, disruptions in piped water supply and depletion of fuelwood. Several spatial aspects influence the intensity at which shocks, and stresses are experienced, these include exposure to climate threats, land use intensity, quality of natural capital and remoteness. Adaptive responses appear to be limited, and mediated by financial capacity, land assets, educational status and social connectivity. Adaptive capacity within communities does not appear to be sufficient considering the number of maladaptive responses found, all pointing to resource insecurity. Insights could be used to target future interventions to support sustainable research management in a way that is both spatially and temporally appropriate for Zanzibar. They could also be used to suggest potential emerging challenges for resources in other small island contexts, especially within the Western Indian Ocean.

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3 COMMUNITY WORKSHOPS: COMMUNITY CENTRED SCENARIOS DEVELOPMENT FOR WATER-ENERGY-FOOD SECURITY ON ZANZIBAR

ABSTRACT

Small developing islands demonstrate strong social-ecological interactions as well as a high level of exposure to climate related effects, which can result in intense land use pressures. Scenario methodologies are useful for reflecting on how competing pressures interact when planning for a more sustainable future. In small islands local knowledge is integral to the development of scenarios because of the close connection between people and local environments. However, local communities are often underrepresented in scenario development processes. This study provides a methodological example of how local knowledge can be used to create scenario themes. Ten community participatory workshops were hosted on Zanzibar (*n* = 142) where a water-energy-food framework was used to examine impacts of environmental change on resource security. Major drivers of land use and land cover change affecting water-energy-food security were identified, these include population growth, development, and climate change. Solutions to observed challenges formed three coherent scenario themes, centred on adaptation, ecosystem health and sustainable settlements. Findings support the idea that communities need space to frame their resource challenges for sustainability planning to work at the appropriate scale.

Keywords: sustainability, livelihoods, climate change, ecosystems, small island developing states, nexus

INTRODUCTION

Communities in small developing islands often depend on ecosystems to meet their livelihood needs, and have become unjustly and disproportionately impacted by rapid environmental change and exposure to climate threats (Nunn and Kumar, 2018). The COP21 statement says that those impacted “must be meaningful participants in and primary beneficiaries of climate action, and they must have access to effective remedies'' (p2). The increasing recognition of the importance of self-determination in decision-making, about both climate change adaptation and sustainability, calls for increased scrutiny on existing participatory methods and how these might better represent those affected. This study focuses on how participatory scenarios development processes could better integrate social-ecological insights from communities by applying a water-energy-food nexus framework at the local scale.

Small islands encompass intense pressures under tight spatial scales. Population growth is frequently concentrated in the coastal margins (Neumann et al., 2015); this exerts pressure on coastal ecosystems such as mangrove and coral rag forests, causing a cycle of degradation and increased exposure to climate related effects such as storm surges, saline intrusion and sea level rise (Barbier, 2015; IPBES, 2018). Environmental pressures related to population growth are coupled with competing land use demands from developing tourism infrastructure (Adger et al., 2009; Lange et al., 2015), as well as climate change, characterised by increased temperatures, drought, erratic rainfall, severe weather events and warming sea temperatures (Mycoo et al, 2022). Adaptive capacity, or peoples' ability to cope with climate change, in response to such challenges is limited in small islands due to their small size, degraded natural resources, low lying topography and geographical isolation (Pelling and Uitto, 2001; Pomeroy et al., 2006); therefore, effective land planning is needed to ensure the long-term environmental sustainability (Huge et al., 2018).

Participatory scenarios can be used to envisage alternative futures and provide an opportunity to explore the unique opportunities and challenges that communities face (Capitani et al., 2016). In summary, scenarios are alternative future pathways created that identify drivers of change and understand potential land use futures which can inform decision making (Johnson et al., 2012; Oteros-Rozas, 2015). Scenario methodologies have become increasingly popular for identifying and addressing potential integrated sustainability challenges for the future (Capitani et al., 2016; Kowalski et al., 2009). For example, they have been used by researchers in the Serengeti to craft pathways for meeting conservation and development goals (Kariuki et al., 2022) and to explore climate-smart options for agriculture in mountains within East Africa (Capitani et al., 2018).

The collaborative process of scenario development fosters multiscale social learning and an appreciation of the complex interactions manifested as land use choices. This helps to sensitise participants to the perspectives and needs of stakeholders at different scales (Kok et al., 2007; Johnson et al., 2012; Oteros-Rozas, 2015; Kariuki et al., 2021) and identify issues that might otherwise be missed or disregarded (Kok et al., 2007; Capitani et al., 2018). Consequently, the process of participatory scenario planning helps strengthen understanding between stakeholders, encourage systematic thinking (Johnson et al., 2012) and enhance opportunities for marginalised communities to participate in decision making (Malinga et al., 2013). This increases the durability and legitimacy of scenarios trajectories (Smith and Stirling 2008; Anguelovski et al., 2016; Scoones, 2016; Brown and Kyttä, 2018).

Whilst community engagement in scenarios processes is highly recommended, it is still limited (IPBES, 2016; Kok et al., 2017; Capitani et al., 2018; Kariuki et al., 2021). Though a number of scenarios studies reference multiple stakeholders, this is often restricted to local expert stakeholders based within institutions, so community members (especially in more rural areas) are not represented (i.e., Shaw et al., 2009; Malinga et al., 2013; Huge et al., 2018). This is especially the case for rural areas, given the adherence to gender roles such as caring for children. As a result, there continues to be a significant imbalance of how the knowledge and needs of local communities are considered within sustainable land use planning (Fagerholm & Käyhkö, 2009). The omission, or ineffective representation, of local knowledge in scenarios outcomes perpetuates the failure of environmental movements to link environmental issues with wider livelihood challenges (Anguelovski et al., 2016; Scoones, 2016).

Barriers to inclusion exist even when local communities participate in scenario planning, as power dynamics influence the consensus building processes and whose voice is heard (Cleaver, 2005). Barriers to participation previously found in small islands include poverty constraints; self-esteem; asymmetrical power relations; and gendered livelihood roles (Gustavsson et al., 2014; Brown and Kyttȁ, 2018). These barriers need to be addressed to enhance the capacity of local communities in decision making processes and represent complex social-ecological dynamics (Cleaver, 1999; Gustavsson et al., 2014). If alternative points of view are not represented and captured in outputs, inequities may be hidden and continued (Oteros-Rozas, 2015), thereby overlooking the inequality of adaptive capacity and exacerbating unequal outcomes in sustainability planning (Hodson and Marvin, 2010; Anguelovski et al., 2016). Consequently, there is still a need to enhance the capacity of local communities in the scenario process (Capitani at al., 2018). This requires acknowledging the value of local knowledge in political and institutional decision making processes, as well as the importance of inclusive land use planning.

This study creates a locally informed framework for scenario development which frames challenges and opportunities for sustainability from a community perspective using a water-energy-food nexus lens. The core objectives of the study are to: (1) identify key land use transitions which have or are expected to affect resource security and livelihoods, through the effective solicitation of local knowledge and (2) develop themes for scenario development, based on what communities' feel are the appropriate actions for mediating experienced or expected challenges. In doing so results from this study will be able to inform future multi-stakeholder scenario processes and align planned adaptation with locally derived experiences and ideas (Juhola et al., 2016; Duvet et al., 2017; Rahman and Hickey, 2019).

Conceptual framework: using a water-energy and-food nexus lens for participatory scenarios development

People and environments are intrinsically linked in small developing islands as people interact with natural and biophysical resources to meet livelihood needs (Douglas, 2006). Strong social-ecological relationships can be due to the relative isolation and limited livelihood options (Ferrol-Schulte et al., 2013). This is especially true for rural low-income groups who are typically more dependent on natural resources (Douglas, 2006; Suckall et al., 2014; Moshy et al., 2015; de Jong Cleyndert et al., 2021).

Considering the dependence on the natural resource base and vulnerability context, a sustainable livelihoods approach can be appropriate for exploring social-ecological interactions on small islands (Ferrol-Schulte et al., 2013). However, the nature of livelihoods in small islands are complex, usually operating at a household rather than individual level and encompassing diversification, often as a result of seasonality (i.e., stormy weather rendering fishing unsafe, growing seasons for crops) (Pomeroy et al., 2006).

This study uses a water-energy-food framework to examine with communities the impacts of environmental change on livelihoods and resource security with the aim of identifying land use transitions and informing land use planning. Chambers and Conway (1992) define a livelihood system as the capabilities, assets (including both material and social resources), and activities required for a means of living. Water-energy-food are seen as essential resources that sustain life and livelihoods (Nhamo et al., 2019). Therefore, knowing how people attain water-energy-food security is crucial for understanding the sustainability of livelihoods (Biggs et al., 2015). In this study, the term 'resource security' is used with an understanding that this feeds into the sustainability of livelihoods more broadly.

The water-energy-food nexus is especially useful for exploring sustainability in small islands because of the short time lag between ecological or social disturbance and imbalances in resource security (Winters et al., 2022). By exploring interactions between water-energy-food it is possible to identify synergies and trade-offs for resource security and livelihoods (Miralles-Wilhelm, 2014). Consequently, it has been recognised as an important framework for decision makers to evaluate sustainability and implement effective policy, which limits significant trade-offs (Keairns et al., 2016).

Land use and land cover change has multiple implications, both positive and negative, across the water-energy-food nexus (Wolde et al., 2021). How these interactions interconnect in island specific contexts and the effect on resource security and livelihoods is still not well understood. This study implements participatory scenarios at the community scale to understand how environmental change impacts resource security and livelihoods and to identify tangible solutions, which could be implemented to respond to actual and emerging challenges. In doing so it begins to tackle the limited involvement of local knowledge in both nexus research and scenario development (Foran, 2015; Albrecht et al., 2018).

STUDY AREA: THE ZANZIBAR ARCHIPELAGO

This study focuses on Unguja and Pemba, the two main islands comprising Zanzibar, situated in the west Indian Ocean just 83 km from Dar es Salaam (see Figure 8). Zanzibar is a semi-autonomous territory and has a political union with Tanzania but its own administrative government. The islands experience a monsoon climate, with 1600-1900 mm annual rainfall and an average temperature of 27.5°C (DoE, 2009). Rainfall typically falls within two periods, the long rainy season from March to May and the short rainy season between October and December.

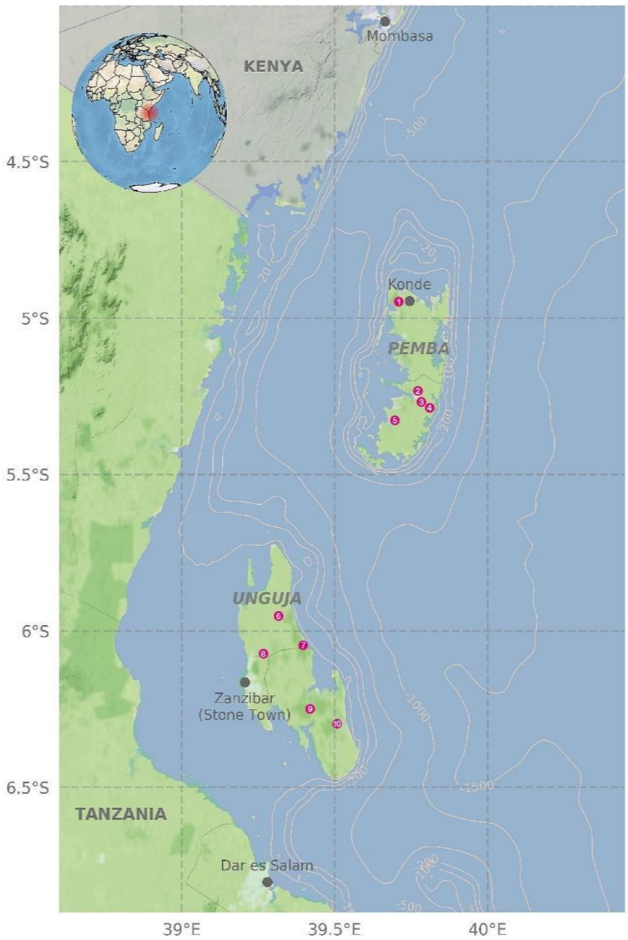


Figure 8. Location of Unguja and Pemba on the East African coastline, map provided by Leclair (2020). Sites in Unguja (left) and Pemba (right), coordinates provided by the Department of Renewable and Non-Renewable Resources, Zanzibar.

Land cover in Zanzibar consists of coral rag vegetation, coastal forests, mangroves, sandy beaches, cultivated forests, tree plantations, woodlands, grasslands, farmlands, parks, settlements and peri-urban and urban spaces (Khamis et al., 2017). Protected forests include Kiwengwa-Pongwe, Jozani-Chakwa Bay and Ngezi forest reserves. Ten mangrove species are found in Zanzibar and are estimated to cover approximately 60 km2 in Unguja and over 120 km2 in Pemba. Despite extraction being forbidden these are under pressure from exploitation, mostly due to over-harvesting for building poles and firewood or charcoal (Yahya, in press). Need for housing, food, income, construction materials, cooking energy and other sources of well-being have resulted in unsustainable pressures on coral rag forests (Käyhkö et al., 2019).

Local livelihood activities, such as deep water fishing, shallow water fishing for octopus, squid, crabs, shrimps and mussels, seaweed farming and more recently sponge and pearl farming, depend upon healthy coastal ecosystems (Suckall at al., 2014). Zanzibar's coral reefs provide important habitat for reef fish and pelagic species (Yahya, in press), as well as coastal protection. However, some of these reefs are endangered due to past destructive fishing practices, tourist activities, pollution and bleaching (Brugere et al., 2020). Seagrass grows in the shallow and intertidal mud and sand flats all around Zanzibar, forming important nursery areas for juvenile fish and foraging areas for herbivorous fish (Khamis et al., 2017).

A substantial proportion of Zanzibar's community rely on subsistence farming to meet household needs, common crops include maize, rice, wheat, pumpkins, millet and beans (Käyhkö et al., 2019). Agriculture employs 42% of the population and contributes a quarter of the country's GDP (RGoz, 2009). Important cash crops include cloves, coconut, mangoes, tomatoes, seaweed and copra. Marine ecosystem services also support the socio-economic system in Zanzibar and account for approximately 30% of the local GDP (Hugé et al., 2018). Tourism activity contributes to 20% of the GDP, and now operates across the majority of the north-eastern coastline (Gustavsson et al., 2014). However, local residents have mostly not benefited from employment, services or economic growth related to tourism (Gustavsson et al., 2014; Käyhkö et al., 2019).

Methods

Participatory scenarios workshops were conducted in ten sites with a cross section of people representing the local communities. Workshops supported communities to reflect on resource and livelihood implications of past change and apply their ideas for managing such issues to the development of alternative scenario visions.

Site selection

The Department of Forestry and Renewable and Non-renewable Resources supported the identification of suitable sites, with an emphasis on sites currently underrepresented in land cover research. The study selected 10 sites in total, with 5 sites in each of the two islands, Pemba and Unguja (Table 8).

Table 8. Details of the workshop locations in terms of areas represented and typical land cover types.

Workshop group location	***Shehia*** **(village) areas included**	Main land cover type represented
Macho Mane	Macho Mane and Mkoroshoni	Peri urban
Mfikiwa	Mfikiwa	Commercial farming
Pujini	Pujini and Dodo	Commercial farming and mangrove cover
Chumbageni	Chumbageni and Wambaa	Coastal area with mangrove cover and some tourism
Mji Mpya	Mji Mpya	Protected forest
Jambiani Kikadini	Jambiani Kikadini	Coastal with high levels of tourism
Pongwe	Pongwe	Coastal with medium levels of tourism and some mangrove cover
Kinyasini	Kinyasini	Peri urban and commercial farming
Kizimbani	Kizimbani	Commercial farming (in particular spice farming)
Pete	Pete	Protected forest reserve and mangrove cover

Participant selection

Village leaders facilitated the engagement of the wider community in the workshops; this was part of the formal protocol for research processes in Zanzibar. Participant selection was purposive to represent both men and women of different age groups. A total of ten workshops were undertaken, the number of participants at each ranged from 9-17 (Pemba *n* = 69 (men 38: women 31); Unguja *n* = 73 (men 39: women 34)).

Amongst the participants the average number of children per household in Pemba was seven and in Unguja five. The most prominent livelihood activities across islands were farming, livestock keeping and fishing (see Appendix 2.1 and 2.2).

Community workshop design

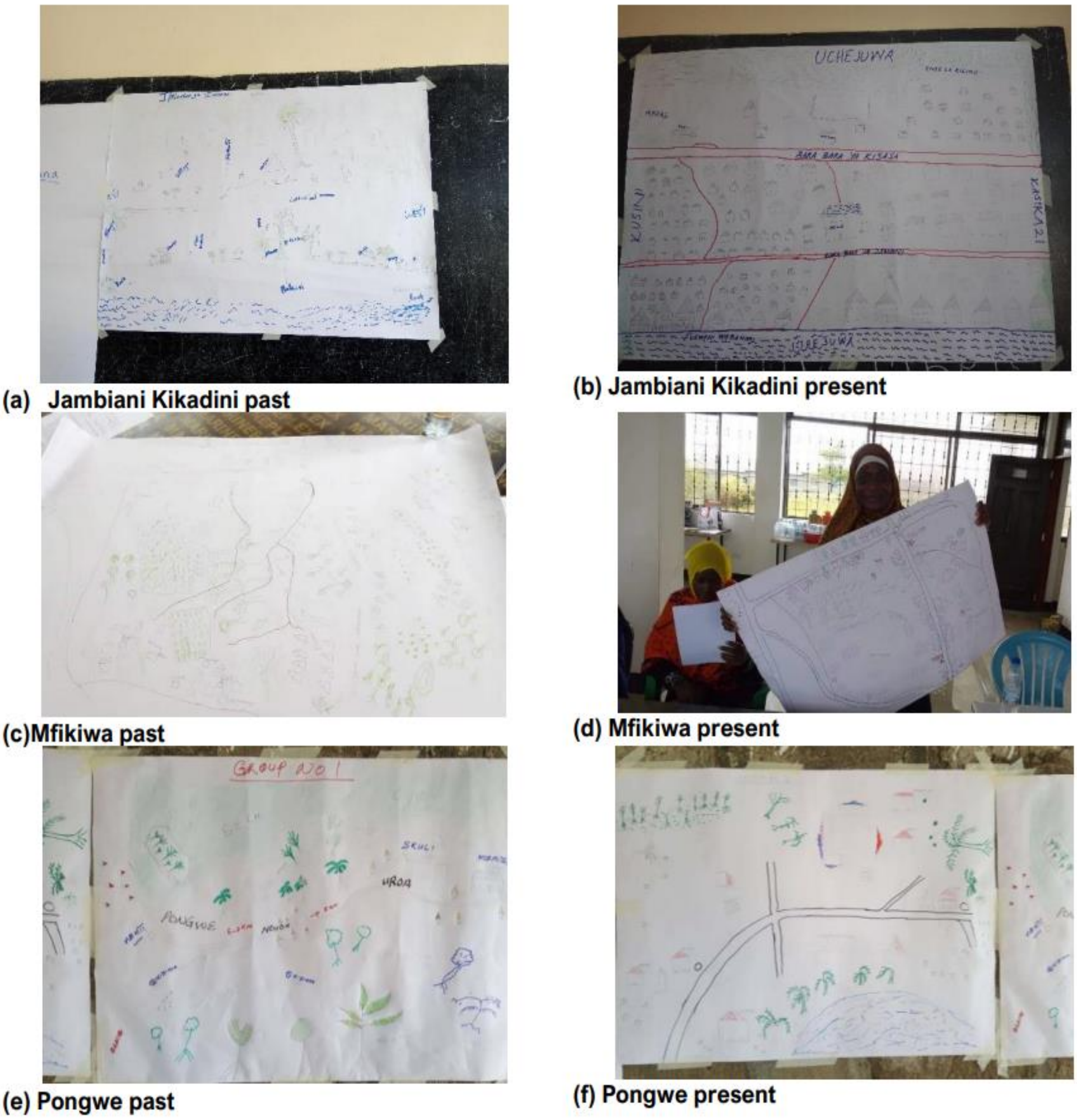
An initial scoping study was conducted with village leaders and elders to develop a foundation of understanding about changes in how communities interact with their environment to meet their livelihood needs and inform workshop design (see Newman et al., 2023). Planning meetings were held with village leaders and elders, in which they selected a date for the workshop and made suggestions about the schedule of the day. Shared control of the planning process helps to ensure that communities feel involved in the research process and shifts some of the power from the researcher to the participants (Castleden et al., 2008). In these early meetings the aims and objectives of the workshop were discussed, this was followed by a tour covering the diverse types of land use in the Shehia's (villages). Images of these were later used in the workshops, as visual data is recognized as an effective tool to foster shared understanding in participatory research (Henwood et al., 2018).

Community-based workshops were the primary means of data collection. They were conducted over the course of one full day in each location to limit the time investment needed by participants. Each participant was remunerated appropriately for their time commitment to cover potential work lost. Refreshments were provided throughout the day and scheduled rest breaks were taken. Participants were made aware of their rights to anonymity and withdrawal, consent forms (written in Swahili) were signed. Participants were all given an order of the day schedule which outlined activities. The workshops were held in Swahili and supported by 1-3 facilitators. All facilitators had undergone a day's training to understand the tasks involved and how to support equal participation across genders and age groups and to assist any participant with literacy difficulties (see Appendix 2.3).

Workshop activities

Participatory land cover mapping

The first activity involved participatory mapping to support knowledge construction around changes in the landscape and to generate discussion around perceived drivers of change. Mapping was used as it can help to identify important places which contribute to water-energy-food security. Consequently, it helps to prioritise future land use management strategies (Fagerholm & Käyhkö, 2009; Brown and Kyttä, 2018). For this activity communities were split into two groups, one group was asked to draw a map of land use and land cover in the village area at present day, the other twenty years ago (Figure 9).



(a) Jambiani Kikadini past
(b) Jambiani Kikadini present
(c)Mfikiwa past
(d) Mfikiwa present
(e) Pongwe past
(f) Pongwe present

Figure 9. Photograph examples of land cover change maps from three of the ten community based workshops.

The two maps were then presented, and the communities compared them in order to identify land cover changes and discuss what they felt were the drivers of change (Figure 10). A list of key drivers was then compiled and displayed on a large piece of paper on a wall. Each individual was given three post-it notes and asked to place them next to what they felt the most significant drivers of change affecting land would be for the future, in order of significance (1 = highest to 3 = lowest). The ranking activity aimed to equalise power when prioritising the significance of drivers.

Figure 10. Photographs of participants working together on identifying changes in land cover and land use and the drivers behind such changes.

Land cover predictions for a Business as Usual (BAU) scenario

Participants were then split into pairs or groups of three and each given images of a specific type of land cover based on photographs taken from earlier village tours. They were asked if they thought there would be any changes to the type of land cover in the next ten years given the identified drivers previously discussed. This period was used to align with the Sustainable Development Goals for 2030, and specifically to inform goals 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable clean energy). They were also asked what the possible impacts could be on the local community and whether there were any solutions which they felt could remedy potential challenges raised. Each group then presented their responses on past and future land use to the wider group.

Water-energy-food security evaluation

During the workshop, each participant was given a form and asked to state their perception of water-energy-food security (1) at present, (2) twenty years ago, and (3) in 2030 with no changes in land use management (BAU scenario). Security was defined by quality (i.e., nutritious value of food, sanitation of water and calorific value of fuelwood) and availability (actual abundance of resources whether it is enough to meet the needs of a community). Participants evaluated water-energy-food security by assigning a number to each criterion (1 being the lowest quality to 4 being the highest). Opportunities to reflect on changes in resource security through the nexus lens aimed to stimulate connections between land use and land cover with livelihood outcomes.

Analysis of workshop outputs

During the participatory mapping activity field notes were taken describing all the drivers of land cover change. These were collated to identify which might be most prevalent in the coming years. Looking at overall prevalence gives a clear indication of areas of focus for national strategies; but results also suggested that drivers differ according to land cover type. To recognise these differences the number one top voted drivers were also delineated according to land cover type.

Strategies for remediating potential emerging challenges relating to land use and land cover change were coded inductively in NVivo to form clustered themes. This involved reading all of the proposed solutions for addressing land cover challenges and grouping similar concepts together, then deciding on an appropriate thematic name which represents each cluster most accurately.

Pearson's chi-squared was used in the R statistical package (version R 3.4.4) to explore whether there was a significant difference in the perceived security of water-energy-food in Unguja and Pemba and across timescales using the participants' individual evaluation scores of quality and availability. The Pearson's chi-squared test explores whether to accept a hypothesis by analysing whether the data deviates from a normal distribution.

T-tests were also performed to determine whether there was a significant difference in these evaluations of water-energy-food security between islands. The chi-squared and t-test analysis aimed to determine which aspects of resource security require most focus and whether policy needs to be differentiated between islands.

RESULTS

Identified land use and land cover changes

Settlement expansion was identified across all sites and associated with deforestation and a reduction in available land for farming. In Jambiani Kikadini village, Unguja the settlement shifted landwards due to sea level rise and the selling of beach plots to hoteliers. This is a pattern that might be replicated in other parts of Zanzibar.

Participants in this study detailed deforestation of coastal mangrove forest areas, commercial plantations for mangos and cloves and coral rag forests as well as around the Ngezi forest reserve (up to the forest boundary). Deforestation was thought to have contributed to reduced water levels in rivers and the drying of oases. It was also linked to a reduction in livestock keeping as people usually keep their animals in the forest.

A number of environmental changes were identified in farming areas, such as reduced soil fertility, limited space, increases in pest and disease outbreaks and lower production resulting from impacts of climate change. Changes in cultivation choices were also identified, including a transition to commercial production, the start of spice farming for ecotourism and a move towards plantation forest for fuelwood in place of food crops.

Other key developments which influenced land use included built infrastructure for schools, healthcare clinics, roads, piped water and electricity. Communities also commented on changes in the quality of housing with the introduction of aluminium roofing and blocks. Whilst these changes were detailed to some extent across all Shehia's on the two islands, the extent of development differed (Figure 11).

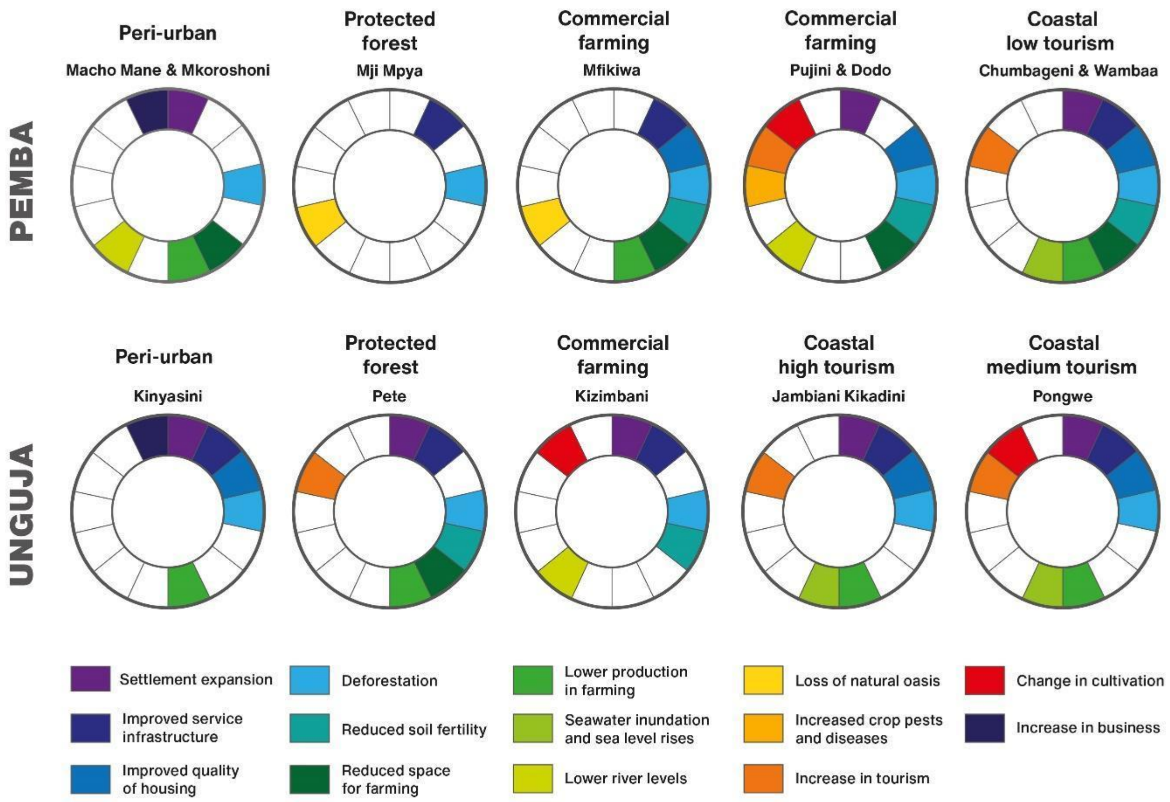
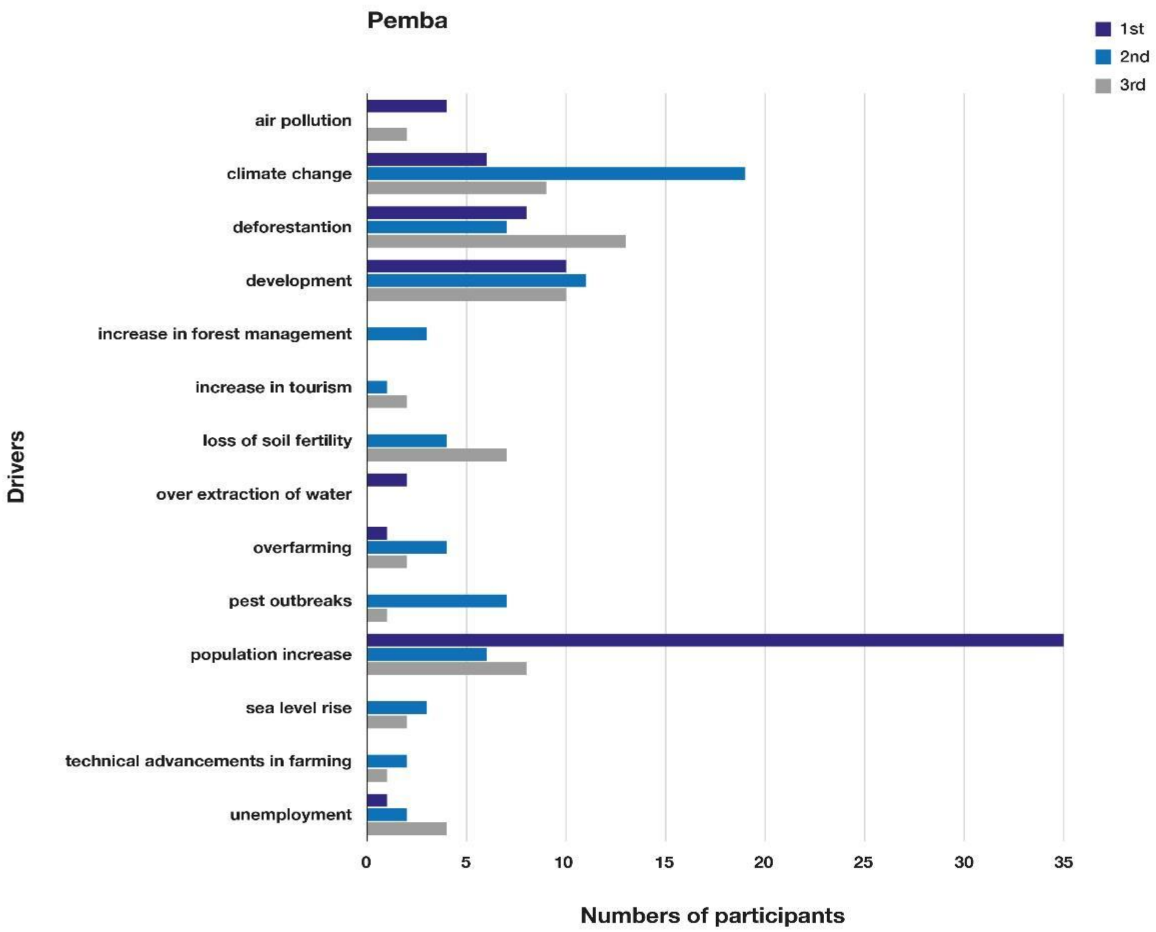


Figure 11. A summary of the land cover changes identified in each of the community based workshops.

Perceived drivers of land use and land cover change

When combining data from across both islands participants identified population increase as a major driver of land use and land cover change (Figure 12 a-b). This was largely because communities rely on natural resources and agriculture to meet livelihood needs. Impacts associated with population increase included over extraction of natural resources, reduced space for farming and increased land use competition due to settlement expansion (see Appendix 2.4).

a.



b.

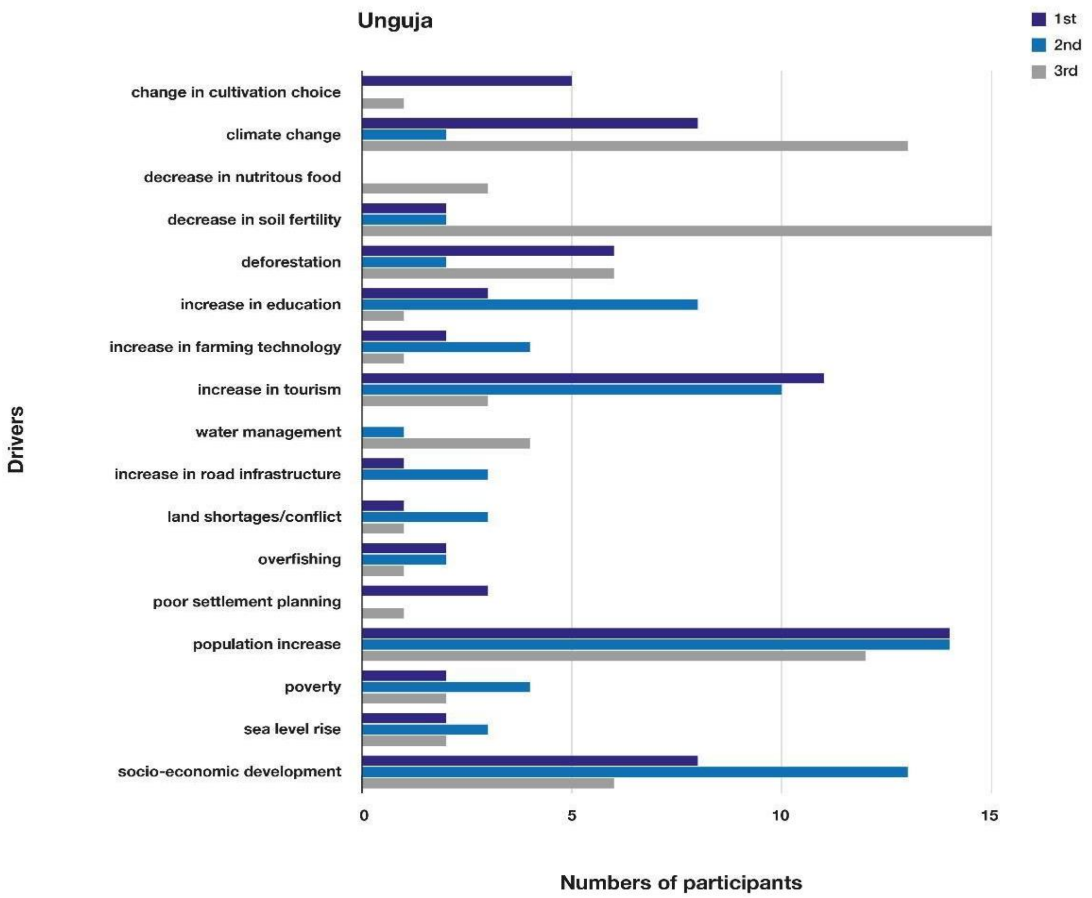


Figure 12. Each participant voted for three of what they thought were the key drivers causing changes which impacted water-energy-food security (1 most influential to 3 least influential – of the three chosen). (a) Top shows the responses for Pemba and (b) Bottom shows the responses for Unguja.

An increase in socio-economic development was also considered a key driver for changes in infrastructure. Development had a direct impact on land cover, but also indirectly caused changes in population dynamics which stimulated subsequent change. For instance, in Kinyasini on the north-east side of Unguja, good connectivity and accessibility provided an opportunity for market expansion, which encouraged more people to move to the area, resulting in settlement expansion. Rates of development were comparatively slower for more remote sites, such as Mji Mpya in Pemba.

In addition, climate change came through as a key driver across sites as it impacted on crop productivity and the ability of communities to meet their basic needs through subsistence farming alone. This related to extended periods of drought and hotter dry seasons which caused crop failure. In some cases, communities outlined challenges of heavy rain out of season which caused an issue for submergence of root crops. In Wambaa, on the coast of Pemba, wave over wash resulted in salinization of agricultural soils causing long term impacts for farming.

Looking at a national level for both islands, population increase, socio economic development and climate change can be considered as the primary factors driving change. However, when delineated by Shehia areas with different predominant land cover types, the perceived number one top drivers differed, showing that a consideration of land cover types is needed for scenarios to capture nuances at local levels (see Table 9).

Table 9. Shows the number 1 top voted driver for each of the main land cover types in Pemba (P) and Unguja (U). Note that Pongwe had an equal result across 3 areas.

	Peri urban		**Coastal**		**Protected forest**		**Commercial farming**	
	P	**U**	**P**	**U**	**P**	**U**	**P**	**U**
Population increase	Macho mane and Mkoroshoni	Kinyasini	Wambaa and Chumbageni	Pongwe			Mfikiwa, Pujini and Dodo	Kizimbani
Deforestation					Mji Mpya			
Increase in ecotourism						Pete		
Increase in tourism				Jambiani				
Change in cultivation				Pongwe				
Socio-economic development				Pongwe				
Climate change		Kinyasini						

Taking into account reflections of past land use and land cover change, several predictions were made to describe a potential BAU scenario. Key changes included deforestation and forest degradation, declining agricultural outputs, a shift away from agroforestry, settlement expansion and an increase in plantation forest (see Figure 13).

Figure 13. Shows predictions of land cover changes in Unguja and Pemba in a BAU scenario alongside the spatial distribution of where these predictions were mentioned.

Water-energy-food security evaluations

Coinciding with identified land use and land cover changes there were significant differences in the perception of quality and availability of water, food and energy between the past (2009), present (2019) and future (2030) (see Tables 10 a-b). The quality and availability of piped water and electricity was thought to have improved from the past (twenty years prior to the workshop) to present day (year of 2019). Fuelwood quality and availability was thought to have declined over time. Similarly, food quality and availability were thought to have declined. In the BAU scenario, the quality and availability of food, fuelwood and well water are all expected to be negatively impacted.

Table 10. The chi-squared results show differences in resource security in (a) Pemba and (b) Unguja.

a. Pemba

Nexus aspect	Chi-squared result for quality
Well water	X^2 = 61.97, d.f. =12, p = < 0.002
Piped water	X^2 = 351.84, d.f. = 12, p = < 0.002
Fuelwood	X^2 = 246.1, d.f. = 12, p = < 0.002
Electricity	X^2 = 321.51, d.f. = 12, p = < 0.002
Food	X^2 = 93.12, d.f. = 12, p = 0.004

b. Unguja

Nexus aspect	Chi-squared result for availability
Well water	X^2 = 61.97, d.f. =12, p = < 0.002
Piped water	X^2 = 333.02, d.f. = 12, p = < 0.002
Fuelwood	X^2 = 258.54, d.f. =12, p = < 0.002
Electricity	X^2 = 329.05, d.f. = 12, p = < 0.002
Food	X^2 = 107.96, d.f. = 12, p = 0.005

There were few differences in the evaluations of overall water-energy-food security between Unguja and Pemba, except for fuelwood quality (t = 3.28, d.f. = 549.78, p = 0.001) and availability (t = 2.75, d.f. = 549.61, p = 0.006). Differences between islands related to their perception of availability and quality for a BAU scenario, with Pemba having slightly more negative evaluations. This was partly because of more optimistic evaluations for future fuelwood security in Pongwe and Kinyasini where communities are already establishing woodlots.

Emergent themes to guide scenario development

Five thematic groups emerge from the coding of 120 proposed solutions. The majority of responses related to improving adaptive capacity, protection and regeneration of ecosystems and sustainable settlement planning, so these are considered to be the three central themes for developing scenarios (Figure 14 a-c). For improving adaptive capacity, there was a strong focus on upskilling in farming and transitioning from subsistence to business farming. As outlined in the workshop in Pujuni:

> *"We must get enough education about best land uses in order to get more food and to do business farming"* (Pujini workshop, April 2019)

For settlement planning participants emphasised the need for better spatial planning, for instance in the Pete workshop participants stated:

> *"We must plan the settlement area in order to keep space for small scale farming and livestock keeping"* (Pete workshop, July 2012)

Another key aspect of the settlement theme was the need to protect cemetery spaces, which could be impinged upon in some areas for development projects. Cemetery spaces are typically forested with coral rag and are used to keep livestock cool. Participants in the Pongwe workshop stated that:

> *"We must hold the environment of the cemetery area, if the cemetery is cleaned, we will lose the animals [livestock], because they will lack water, good air and food they need for strong health"* (Pongwe workshop, July 2019)

Ecosystem protection and regeneration largely centred on forest spaces, with a particular emphasis on mangroves and their wider ecosystem benefits. For instance, in Pongwe, participants said:

> *"There is a need to avoid deforestation along coastlines, if we lose the natural trees close to the sea, we will lose the habitat for the fish, and they will escape because the place they like to play will be demolished"* (Pongwe workshop, July 2019)

Proposed action towards ecosystem protection and regeneration centred on education, including indigenous knowledge sharing.

The other two themes included family planning to reduce population increase and maintaining cultural values. Cultural values related to educating younger generations about places of historical spiritual and cultural importance and includes factors such as good collaboration, unity, and respect within communities and between communities and government sectors. Both of these themes can be considered within all the scenarios options (see Appendix 2.5).

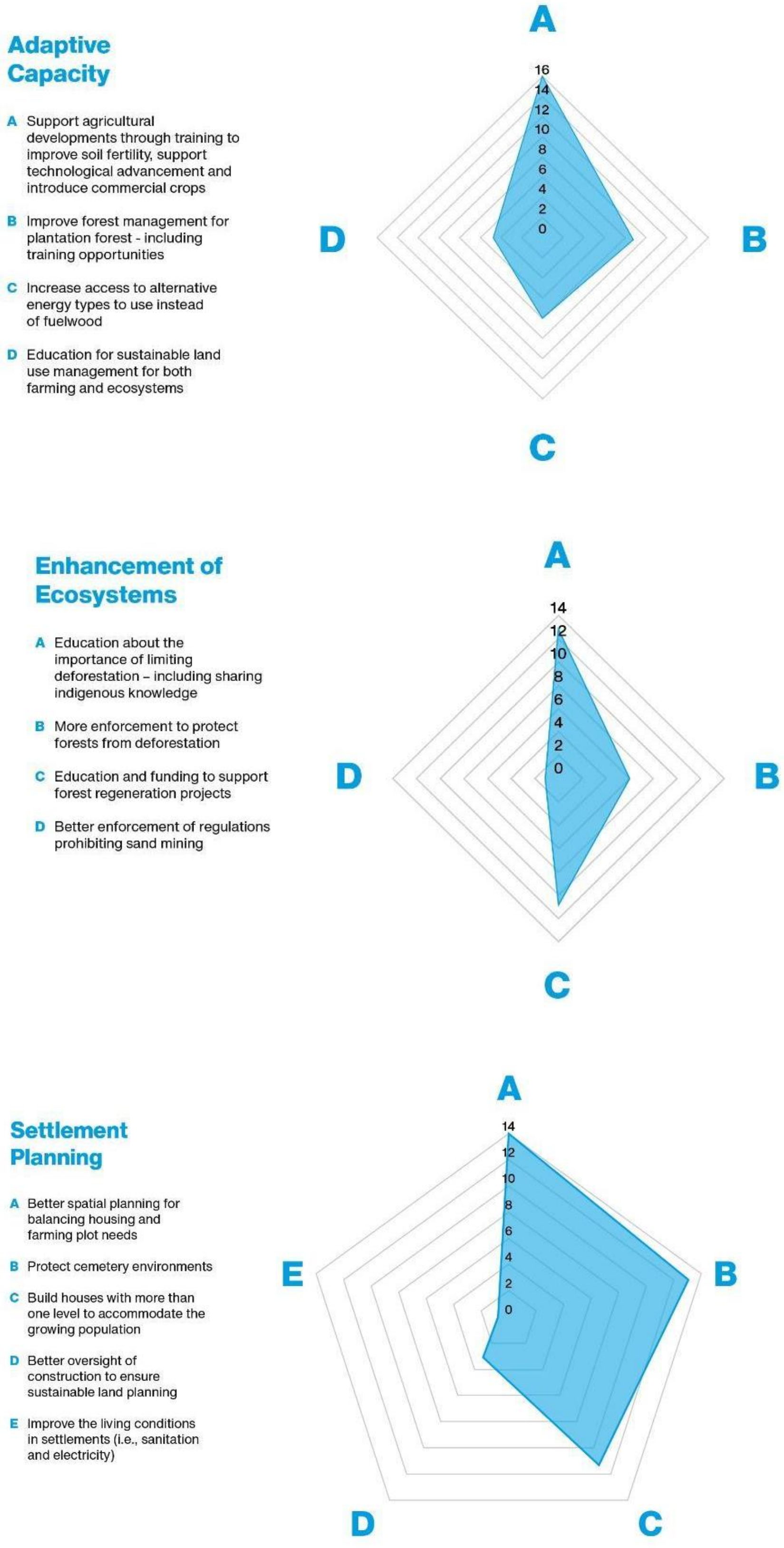


Figure 14. The statements communicated for solutions to research challenges in each thematic grouping as well as the number of times they were mentioned. Results are combined across the two islands.

Discussion

Land cover pressures

Our findings align with other recent research showing that pressures on the coastline are intensified (Mimura et al., 2007; Suckall at al., 2014; Nunn and Kumar, 2018; Mycoo et al, 2022), and degradation of coastal ecosystems increases vulnerability to seawater inundation and intrusion (Mercer et al., 2014; Barbier, 2015). This can be exacerbated by a lack of landscape consideration through the building of hotel infrastructure, which removes protective ecosystems, and often protects individual buildings with sea defences. However, the lack of connectivity of these means that seawater enters the spaces in between hotel buildings with greater force, exacerbating flooding in villages.

In addition to this, our findings also demonstrate that areas farther inland on small islands experience a differentiated set of water-energy-food challenges currently not well represented in wider research in small islands. For instance, results show that factors such as remoteness and land use competition contribute to resource insecurity and therefore warrant more attention. More specifically, this study found that in remote locations communities are often excluded from development transitions, such as electrification, piped water provision and road construction. Inland areas also face increases in commercial agriculture which contributes to land use competition, often leading to high levels of deforestation.

Results from this study indicate how drivers of change emerge slightly differently across spatial scales and uncover some of the reasons for this. Whilst our results align with previous studies by showing that population growth is high at coastal fringes (Neumann et al., 2015), they also indicate that growth is experienced outside of coastal spaces. For instance, in areas with good market connectivity, fertile soils for farming or other areas of natural capital. It is important to understand these dynamics as population growth might contribute to resource pressures inland, where the majority of the population still rely on natural resources to meet their water-energy-food needs. Results further show that coastal challenges are also not homogeneous but differentiated according to location specific pressures, such as tourism. Emerging challenges for resource security are discussed below.

Water security

Our findings indicate that water security is a prevalent ongoing issue because of multiple pressures. Water scarcity is expected to increase due to population growth, urbanisation, tourism and increased aridity (Mycoo et al, 2022). Results show that concerns about over extraction of groundwater are especially high in Unguja. Even in 2001, extraction was found to be unsustainable on the east coast of Unguja due to high water demands from tourism (Gössling, 2001). Overexploitation of the aquifer contributes to the lowering of the groundwater table, land subsidence, poor groundwater quality and saltwater intrusion (Gössling, 2001; Makame et al., 2018). Previous research also found that as new users become connected to piped water in tourist hotpots, such as Jambiani and Nungwi, existing users experience a reduction in the supply (Slade, 2012). This often forces communities to revert back to well water, which has compromised quality due to over extraction and sewage contamination (Slade, 2012).

This study found that though access to cleaner water through piped water infrastructure has been a vital improvement to livelihoods, in terms of both improving sanitation and reducing time spent collecting water, there are growing concerns about the availability and quality of well water. By engaging with communities through our study, it became apparent that well water remains an important backup supply. This back up supply is particularly important because piped water relies on electricity for water pumps and so is affected by power cuts. At times poor maintenance of water infrastructure can also lead to prolonged disruptions in supply. Kondash et al (2021) found that an interruption in piped water supply, even for one day per month, elevates the likelihood of diarrhoea in children to levels comparable to children without piped water. As the intensity of rainfall and ensuing flooding events is expected to increase in East Africa there is an additional associated risk of greater exposure to waterborne diseases such as typhoid and cholera due to damage to water systems (Mycoo et al, 2022). Therefore, our results indicate that there is a need to both monitor and maintain the quality of well water as well as the robustness of piped water systems, especially given predictions about more extreme conditions.

Considering the water demand in Zanzibar, more effort is needed to address issues of over extraction related to tourism. This is not a new or emerging issue; both Gössling (2001) and Slade (2012) advocated for water mandates on hotels, including rainwater harvesting, use of greywater, adequate treatment and disposal of sewage, limited provision of swimming pools (or use of saltwater pools), desalination of seawater, limited laundry of towels and linen, use of drought resistant plants in landscaping. Zanzibar's 2012 Coastal and Marine Tourism Management Plan objectives also included the encouragement of eco-lodges with rainwater harvesting plans in areas with limited or no water supply and the implementation. However, since then the number of tourists visiting has increased and there continues to be inadequate regulation of water use. Whilst there is more of an awareness of the impacts of tourism demand on water resources, there is a greater need to also explore how water is managed in agricultural systems to make more efficient use of it.

Energy security

Findings show serious concerns about the sustainability of fuelwood extraction. Communities across both islands predict that land use pressures will affect land use and land cover by increasing levels of deforestation across all forest types. As coral rag forests have become increasingly deforested and degraded, deforestation is spreading to other forest types including mangrove and plantation. Implications of the degradation and deforestation of coral rag forests include loss of biodiversity, reduction in the availability of forest products and lowering of the groundwater table (Nowak and Lee, 2009; Ahmed and Mishra, 2020). In the case of mangroves, communities in this study showed concern about coastal erosion, seawater inundation and salinisation of ground water and agricultural land - this has also been evidenced across other small developing islands (Veitayaki et al., 2017). Continued degradation of both marine and terrestrial ecosystems is anticipated to exacerbate island communities' vulnerability to climate change impacts, such as cyclone and sea level events, which are predicted to increase in the coming decades (Barbier, 2015; Mycoo et al, 2022).

Although communities have seen an increase in electrification, poverty limits the utilisation of this, and fuelwood remains the main energy source. Some communities represented in our workshops are initiating woodlots to establish more secure supplies of fuelwood; yet the extent to which this can meet the needs of the wider population is not currently well understood. More broadly, small developing islands are considered especially vulnerable to energy insecurity as they rely on imported fossil fuels with high import costs, lack of energy infrastructure, unequal distribution and over reliance on depleting biomass sources (Raghoo et al.,2018; Suroop et al., 2018); which could limit communities potential to transition to electricity. Renewable energy has been recommended for small islands contexts to reduce exposure to price volatility of fossil fuels (Lucas et al., 2017). This is all the more pertinent given the rising prices of fossil fuels seen globally in 2022 and the continued unsustainability of fuelwood extraction to provide energy security to a growing population.

Food security

Communities across all sites in our study explained that food insecurity was a growing issue. At the start of 2023 the President of Zanzibar even introduced a ban on food exports from Zanzibar to curb food shortages and price hikes. Small developing islands are vulnerable to food security as they are net importers of food and therefore exposed to global price fluctuations (Pelling and

Uitto, 2001). The capacity of small island communities to produce their own food is limited by climate change effects including increased temperatures, longer dry seasons, changing rainfall regimes, inadequate freshwater supplies, sea-level rise, saltwater intrusion, increased health risks (e.g., water- and vector-borne diseases), land loss and degradation, coastal erosion, and coral bleaching (Mimura et al., 2007; Mercer et al., 2014; Mycoo et al, 2022).

Existing research has demonstrated that increased heat and drought has increased across most of Africa. In East Africa specifically rainfall is predicted to become less frequent but more intense with increased wind speeds causing increased levels of crop failure (Trisos et al, 2022). In addition to this, research in Zanzibar has shown that agricultural declines and erratic fishing yields has pushed households towards a greater dependence on markets for staple food supplies; this makes households with low purchasing power especially vulnerable (Makame et al., 2015). By engaging with communities, our results revealed that people's relationship with food is also altered as they have less oversight of the growing and processing of foods as a result many people felt less confident about its quality and nutritional value.

Integration of results with wider scenarios research

Scenario themes developed by communities to address land use challenges which influenced resource security intersect in some places with wider research on small islands, as well as other environments with strong social-ecological interactions. Communities suggest that there is a need for both regeneration and protection of coastal vegetation, as well as better spatial planning; these scenario objectives align with priorities generated in workshops involving coastal science and management experts in Unguja (Huge et al., 2018). Improving adaptive capacity through developing multifunctional landscapes, which support both biodiversity and humans, is considered to be one of the most desirable scenarios in mountain communities (Lebel, 2006; Capitani et al., 2018; Carvarlho-Ribeiro et al., 2010; Thorn et al., 2021). Mountain communities face similar pressures to small island communities, such as geographic isolation and resource dependence. Previous research in mountain communities in South and East Africa has also shown the importance of cultural values and opportunities for Indigenous knowledge sharing combined with innovation in scenario development (Malinga et al., 2013; Thorn et al., 2021). Cultural values such as unity and collaboration came through in scenarios for Zanzibar, which emphasises the importance of social connectivity in small islands (Pelling and Uitto, 2001). Also, in line with suggested scenarios in Zanzibar, environmental integrity was identified as a desirable scenario from communities in northern Tanzania (Kariuki et al., 2021). Whilst place-specific insights should guide scenarios at finer scales, these alignments could be used to inform wider policy planning for the Sustainable Development Goals (SDG's) and the longer term African Union 2063 Agenda.

Future application

Inadequate representation of communities in sustainability planning can result in inappropriate action for addressing resource challenges (Juhola et al., 2016). This study attempts to situate communities more centrally in the formation of scenarios by providing an opportunity for them to frame their resource challenges and create themes for developing scenarios based on solutions which they feel would be effective. These insights need to now be integrated with multiscale strategies to enhance the agency of communities within decision making processes which guide policy formation (Hickey and Mohan, 2004). Next steps should involve multi-stakeholder workshops, including representatives from institutional bodies and communities, to discuss how the suggested scenarios could be realised whilst considering potential barriers. This would provide an opportunity to integrate insights on regional, national and global drivers of change and potential bodies and resources to address change. Results could also be used to bring community perspectives into Zanzibar's 2050 Vision, which encompasses aims in line with both the Sustainable Development Goals for 2030 and the African Union Agenda for 2063. This would help to ensure that experiences and insights at the community level feed into tangible land use decisions.

Limitations

This study aimed to recognise the agency of communities in scenario development for sustainable land use by creating an opportunity for communities to frame resource challenges and solutions. While this addressed barriers to inclusion such as: self-esteem, financial limitations and power dynamics between experts and community members, there are some limitations which need to be considered. These workshops included those with positions of power at the community level, hierarchical structures are well respected in Zanzibar, so this could mean people are not likely to propose an alternative viewpoint in open discussions. Also, because of the nature of research protocols in Zanzibar at the time, village leaders were responsible for engaging participants; this could potentially lead to the selection of people representing just one political party or perspective. Because a small remuneration was paid for participation it could also have resulted in family members or close friends being invited over other members of the community. Consequently, it is possible that more marginalised people were not included and there is still a need to include less represented groups, such as migrants and disabled people.

Conclusion

Islands in Zanzibar are facing land use and land cover pressures, due to climate change, population increase and development, all of which impact resource security. Whilst interaction between local communities and environments in small islands is strong, local insights need to be drawn upon to inform scenario development. Barriers to inclusion involve poverty, self-esteem and unequal power between those representing institutions and community members. To address these issues, community workshops were held on-site with community members only to frame resource challenges and form themes to build upon in multi-stakeholder workshops. By including communities from diverse landscapes across Zanzibar, a greater understanding of differentiated land use and cover challenges for water-energy-food security was unveiled. Three clear scenario themes emerged in response to the sustainability context: improving adaptive capacity, sustainable settlement planning and protection and regeneration of ecosystems. These findings could be used to create locally relevant sustainability priorities which address emerging resource challenges in Zanzibar.

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4 'KESHO' SCENARIO DEVELOPMENT FOR SUPPORTING WATER-ENERGY FOOD SECURITY UNDER UNCERTAIN FUTURE CONDITIONS IN ZANZIBAR

ABSTRACT

Social-ecological interactions mediate water-energy-food security in small developing islands, but community scale insights are underrepresented in nexus research. These interactions are dynamic in their response to environmental and anthropogenic pressures and need to be understood to inform sustainable land use planning into the future. This article centred on bringing together diverse stakeholders to explore water-energy-food futures using the "Kesho" (meaning "tomorrow" in Kiswahili) scenario tool for two of the largest islands that comprise the Zanzibar Archipelago. The methodology comprised of four core stages: (1) exploration of how past drivers of change impacted water-energy-food security; (2) modelling of a Business as Usual scenario for land cover change (3) narrative development to describe alternative futures for 2030 based on themes developed at the community scale; (4) predictions about how narratives would shape land cover and its implications for the nexus. These results were used to model alternate land cover scenarios in TerrSet IDRISI (v. 18.31) to produce visual representations of expected change. Findings demonstrated that deforestation, saltwater incursion, and a reduction in permanent waterbodies were projected by the year 2030 in a *Business as Usual* scenario. Three alternative scenario narratives were developed, these included *Adaptation, Ecosystem Management* and *Settlement Planning*. Results demonstrate that the effectiveness of actions under the scenario options differ across the islands, indicating the importance of understanding the suitability of national policies across scales. Synergies across the scenario narratives also emerged, these included: integrated approaches for managing environmental change, community participation in decision-making, effective protection of forests, cultural sensitivity to settlement planning, and poverty alleviation. These synergies could be used to plan strategic action towards effectively strengthening water-energy-food security in Zanzibar.

Keywords: livelihoods, nexus, climate change, development, ecosystems, western Indian ocean

INTRODUCTION

The interactions amongst land use, climate and socio-economic changes impact the resilience and sustainability of social-ecological systems (Kariuki et al, 2022). In small islands within the Western Indian Ocean (WIO), shifts in these dynamics have significant impacts for livelihoods and resource security - particularly as they are concentrated over smaller spatial extents (Poti et al, 2022). Small islands in this region are undergoing rapid changes related to transitions to industrial fishing, exploitation of gas and oil, expansion of tourism and urbanisation – all of which degrade ecosystems and water resources that support local livelihoods (Laffoley et al, 2020).

Alongside social changes, climate change poses significant threats to local economies, many of which are informal. Communities on small islands are vulnerable to impacts such as sea level rise, coastal erosion, drought, high wind speeds, erratic rainfall and changes in sea temperature and acidity. Climate change also poses a threat to the unique biodiversity of the WIO, including its coral reefs, seagrasses, and mangroves, which are vital for coastal protection and supporting marine life (International Panel on Climate Change, 2022).

As well as facing more incremental changes associated with climate change, communities living on small islands are exposed to natural hazards that include heavy rainfall, droughts, extreme high temperatures, storm surges, cyclones and tsunamis (Mycoo et al, 2022). All these pressures impact people and the way they interact with their environment to meet their needs (Newman et al, 2023).

There is a growing awareness that in these contexts' knowledge exchange and integration of local experience into decision making is key to building adaptive capacity (Poti et al, 2022). Participatory scenarios can be used to consider how to manage causes and consequences of complex social-ecological challenges, as they offer an opportunity to explore multiple and interacting pressures, alongside effects on livelihoods (Kariuki et al, 2022; Marchant, 2022; Thorn et al, 2021b). Scenarios are useful in the context of small island states for several reasons. By simulating different future conditions, scenarios can inform strategies, investments and plans that are robust under a range of potential futures (Kariuki et al, 2022). They can also help to pre-empt conflicting agendas and prepare for external influences (Haasnoot et al, 2013, Hermans et al, 2017, Lavorel et al, 2019). This could support the building of adaptive capacity of communities on small islands in response to social-ecological changes.

In a small island context, a water-energy-food nexus approach is critical for evaluating synergies and trade-offs of different land management decisions, given that they operate at tight spatial scales and effects can be rapid (Winters et al, 2022). The water-energy-food nexus recognizes systems are interconnected and interdependent. For example, in coastal island communities, water is essential for hydropower dams, and irrigating agricultural areas, while energy is needed to pump, desalinate, treat, and distribute water as well as produce, process, preserve and transport food (Newman et al, 2023; Winters et al, 2022). Another example is forests and their role in protecting coast-lines from inundation which results in the salinization of agricultural soils (Newman et al, 2024) as well as available groundwater resources (Barbier, 2015).

Analysis of the resource system allows the identification of effective policy for improving adaptive capacity (Kurian, 2017; Mpandeli et al, 2018). For instance, previous research in Zanzibar identified solar as an important energy transition to disentangle from expensive dependencies for electricity from mainland Tanzania and ensure consistent pumping of water (Dean, 2023). An integrated approach to exploring resource security across sectors could therefore potentially better inform where priorities are set and shifted.

Despite this need, there are a limited number of emergent studies exploring future options to support a sustainable water-energy-food nexus in small islands (i.e. Winters et al, 2022; Martin del Campo et al, 2023; Crisman & Winters, 2023). Even then, the studies have tended to focus on broad system levels and do not capture more in-depth local interactions. This is an important gap to consider given that social-ecological changes have multiple impacts across the water-energy-food nexus (Albrecht et al, 2018).

Considering that there are several layers of understanding needed to fully unveil opportunities for addressing sustainability challenges, multiple perspectives from diverse stakeholders across scales and levels are needed. These include power hierarchies, access to knowledge and capacity, and can be nested across scales (Cleaver, 2005; Gustavsson et al, 2014). This would not only improve the feasibility and validity, but the uptake, and concreteness of scenarios (Saito et al, 2019; Thorn et al, 2023). By positioning future scenarios around the water-energy-food security nexus this study attempts to respond appropriately to local needs.

The purpose of this research was to create scenario alternatives to address actual and emerging challenges for water-energy-food security experienced by local communities in a small island context. There were three core objectives: (1) to explore how key drivers of change operate spatially and temporally; (2) to develop coherent and tangible scenario narratives using alternative themes generated by communities; *Ecosystem Management*, *Adaptation* and *Settlement Planning;* and (3) to model land cover implications for water-energy-food security towards 2030.

Findings also unveil alignments in strategic areas of focus for responding to and preparing for change across scenario narratives. Consequently, results could be used to help inform planned action towards achieving the 2030 Sustainable Development Goals (Sustainable Development Goals, 2015), and national policy documents such as the Nationally Determined Contributions the National Biodiversity Strategy and Action Plans feeding into the United Nations Framework

Convention on Climate Change and Convention on Biological Diversity UN CBD process, as well as inform areas of action which align with the Zanzibar Development Vision for 2050 (Zanzibar Planning Authority, 2020) .

METHODS

Study area

Zanzibar, a semi-autonomous territory which forms a political union with mainland Tanzania, is an archipelago in the Indian Ocean (Figure 15). Although census records are dated, the population growth rate was c. 3.1% in 2013, but expected to fall to 2.8% by 2035 (OCGS, 2015). Most of this population growth has been in urban areas, with growing disparities in welfare between the islands of Pemba and Unguja. Poverty levels based on household consumption stand at 25.7% (World Bank, 2022).

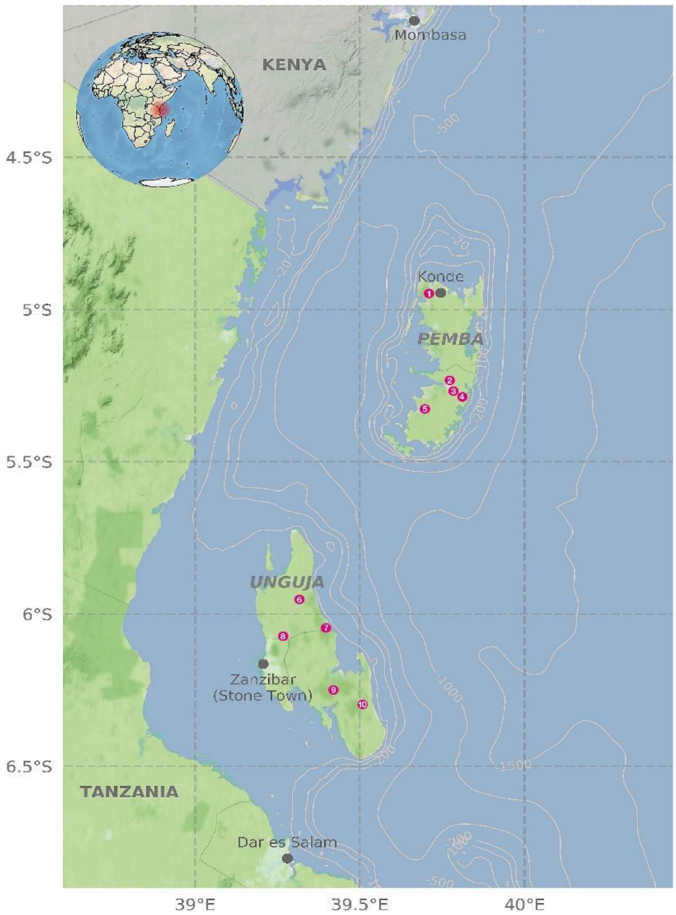

Figure 15. Location of Unguja and Pemba on the East African coastline, original map provided by Leclair (2020) and adapted by Newman et al (2023b) to include community based workshop sites in Unguja (left) and Pemba (right). Members of each of these communities were included as stakeholders in this study. Coordinates provided by the Department of Renewable and Non-Renewable Resources, Zanzibar.

The islands have a humid tropical monsoon climate with 1600–1900 mm annual rainfall and an average annual temperature of 27.5 °C (DoE, 2009). There are four main seasons: “kaskazi” (hot season) between December and February; “masika” (long rainy season) between March and May; “kipupwe” (cold season with high winds) between June and September; and “vuli” (short rains) between October and December. Though climate variability is changing these more predictable patterns (Makame & Shackleton, 2019).

Key livelihoods include farming, fishing, and seaweed aquaculture (Suckall et al, 2015). The islands are experiencing fast rates of change, stimulated by population growth, in migration, urbanisation, tourism and increased land demand for agriculture and forestry products (Kukkonen and Käyhkö, 2014). Although tourism contributed to 29.2% of the GDP in 2022, resulting in the investment in key services, for some villages, high levels of tourism have resulted in loss of access to beach and sea, resulting in a loss of livelihoods (Lange, 2015).

Freshwater lenses above saltwater are the main freshwater sources on Zanzibar (Ali et al, 2021). Only 24% of rainwater is captured into groundwater, as approximately 44% evaporates and 32% as surface runoff (Haji, 2010). Only 1.3% is captured for domestic and irrigation purposes through rainwater harvesting and remains underutilised on the island (Government of Zanzibar, 2007). Recent research has indicated that groundwater abstraction in Unguja island is higher than the rate of recharge. This means that groundwater is overexploited and exposed to pollution and saltwater intrusion (Ali and Rwiza, 2020). Seasonal imbalances occur during the dry season when recharge is at its lowest, but abstraction rates are at their highest due to demands from tourism (Gössling, 2001; Ali and Twiza, 2020). Saltwater intrusion is already widespread due to the pumping of groundwater from coastal aquifers (Mato, 2015). Water is generally abstracted from springs and caves and supplied to communities through pipelines and public taps (Gössling, 2001).

Zanzibar’s electric grid is reliant on hydroelectricity generated on mainland Tanzania, which is carried through two underwater cables, one with a capacity of 100 megawatts to Unguja and another 25 megawatt cable to Pemba island (Winthers, 2013). Each island has substations to redistribute this electricity with significant wattage loss (Dean, 2023). Demand for electricity is set to exceed the cable capacity in the next few years, with development outpacing capacity (Dean, 2023). Because Zanzibar's electricity is generated in Tanzania, ZECO, the Zanzibari electrical distributor, pay’s Tanzania Electric Supply Company (TANESCO, Tanzania's electrical provider) each month for the megawattage received (Dean, 2023). To lessen the reliance on Tanzania for energy needs, Zanzibar has set a target of using 30% local renewables by 2030 (Dean, 2030).

Food security is a major issue in Zanzibar with approximately 65% of households experiencing poor food consumption and 32% being severely food insecure (Nyangasa et al, 2019). Many households in Zanzibar depend upon subsistence activities, such as fishing and farming, to meet their food needs and are highly exposed to food insecurity because of stressors such as climate change alongside increased food demands from tourism (Makame et al, 2015).

Research approach

The approach for research was based on principles outlined by a scenario analysis tool called "Kesho" (Capitani & Marchant, 2019). Kesho provides a structured framework allowing participation of diverse stakeholders across scales to connect their insights directly into land cover modelling. The method has been applied in the Southern Agri-cultural Growth Corridor Kilombero, southwest Tanzania (Thorn et al, 2022), in the Serengeti Landscape on pastoral transitions (Kariuki et al, 2022), to assess natural capital in Tanzania (Capitani et al, 2019a) and evaluate mountain social-ecological system transitions in Kenya and Ethiopia (Capitani et al, 2019b).

In the case of this research, objectives of working towards water-energy-food security were developed through ethnographic research and confirmed after focus groups with village leaders and elders (number of participants (*n*) = 40). Transcripts and field-notes of these discussions were inductively coded and emergent themes used to guide the rest of the research process (see Newman et al, 2023). Boundary conditions were spatially set to island level in Unguja and Pemba and temporally to the year 2030 to coincide with the 17 Sustainable Development Goals and the first-time horizon for Zanzibar's Development Vision for 2050 (ZPA, 2020).

In the second stage, which took place from April to August 2019, scenario themes were co-developed by communities, in community-based workshops in ten villages across the two islands (*n* = 142) (see Table 11). Communities went through a process of identifying key drivers of change and the impacts of land cover change on water, energy, and food. They made predictions for how drivers might contribute to challenges for water-energy-food security in the future. They then suggested several strategies which would be used to mediate these. The clustering and prioritisation of these strategies led to three core themes to frame future scenarios, *Ecosystem Management, Adaptation* and *Settlement Planning* (Newman et al, 2024).

The third phase, which is detailed here, involved scenario modelling, starting with land cover modelling of a *Business as Usual* scenario based on insights from the community-based workshops to inform variable section for causes of land cover change. This was followed by two scenarios workshops which took place in October of 2019, and involved both expert stakeholders and community representatives who created narratives for alternative sustainable scenarios. In these workshops, participants predicted how each of the alternative scenarios would alter land cover and the impact this might have on water-energy-food security for 2030 (n = 67). Land cover predictions made by participants were modelled to create spatially explicit visualizations of the scenarios centred on stakeholder perspectives.

In previous Kesho applications, scenarios multistakeholder workshops have explored the *Business as Usual* scenario in tangent to sustainable alternatives in multistakeholder workshops. In this case the *Business as Usual* model was created using insights from community based insights and then used as a reference point for predicting land cover change in other scenarios (i.e., "30% less built up transitions than a BAU scenario). This was decided so that collaboration and co-creation amongst diverse stakeholders could focus on solutions and how to work towards positive outcomes.

Table 11. Community workshop locations for the pre multi-stakeholder workshop preparation (Newman et al, 2023b). Locations represent diverse land cover types across both islands. The first five locations are on Pemba Island, the last five locations are on Unguja island.

Workshop group location	***Shehia* (village) areas included**	**Main land cover type represented**
Macho Mane	Macho Mane and Mkoroshoni	Peri urban
Mfikiwa	Mfikiwa	Commercial farming
Pujini	Pujini and Dodo	Commercial farming and mangrove cover
Chumbageni	Chumbageni and Wambaa	Coastal area with mangrove cover and some tourism
Mji Mpya	Mji Mpya	Protected forest
Jambiani Kikadini	Jambiani Kikadini	Coastal with high levels of tourism
Pongwe	Pongwe	Coastal with medium levels of tourism and some mangrove cover
Kinyasini	Kinyasini	Peri urban and commercial farming
Kizimbani	Kizimbani	Commercial farming (in particular spice farming)
Pete	Pete	Protected forest reserve and mangrove cover

The third phase, this study, involved both expert stakeholders and community representatives creating narratives for each of the scenarios, predicting how they would alter land cover and the impact this might have on water-energy-food security for 2030. Land cover predictions were modelled to create spatially explicit visualisations of the scenarios centred on stakeholder perspectives.

Participant selection

Two full day scenario workshops were undertaken with local stakeholder participants, three Swahili speaking facilitators, and the author, one in Macho Mane Pemba (*n*=44) and one in Stonetown Unguja (*n*=23). Stakeholders involved community representatives from all ten previous sites (one man, one woman and the "*Sheha*" (village leader)). These stakeholders had been originally recruited by each village leader across the village sample sites, and then selected by communities in the community based workshops to represent them in the multi-stakeholder workshops.

Members from agriculture, forestry, environment, water, energy, and tourism departments in Zanzibar attended, alongside two Non-Governmental Organisations, Milele Foundation (a sustainable livelihood organisation) and Wildlife Conservation Society. These stakeholders were recruited through the support of fieldwork facilitators based at the Department of Forestry and Renewable and Non-renewable Resources in Zanzibar.

At the Pemba workshop, 37% of the participants were women and 63% men. In the Unguja workshop 48% of the participants were women and 52% men; this was achieved through specifying to community leaders and ministries that we were aiming for equal gender representation. At the village level, three out of ten village leaders were women, suggesting a move to more equal participation of women in leadership roles.

The participants were split into three working groups in each scenario workshop. These were organised to mix both community representatives and representatives from institutions together. Three Swahili speaking facilitators supported the groups throughout the day, assisting those who were unable to read or write and explaining activity instructions.

All facilitators had undergone a day's training with the lead author in the week preceding the workshops to become familiar with the workshop activities. During this training the need for identifying participant needs and encouraging participation across age, gender and background was discussed. Facilitators were asked to keep a record of any imbalances in contributions that they became aware of during the workshops.

Workshop activities

Water-energy-food context

Timelines were produced in which drivers of land use and land cover change influencing water-energy-food were identified from 40 years ago to the present day. Participants were asked to consider environmental, social, economic, technical, and political drivers of change to avoid sectoral biases. The timeline was used on a horizontal axis and on the vertical axis trends in water-energy-food security were drawn. Each group discussed how the events on the timeline contributed to these trends and made notes on points made.

Spatial mapping of drivers

Groups reflected on the scale at which different drivers of change might be felt across the island (Unguja or Pemba) by 2030. Each group was given a blank map which just detailed "*Shehia"* (village) boundaries. Group one coloured and labelled areas in the island (Pemba or Unguja) where population growth would likely be highest and explained why. Group two did the same for climate change and group three for development.

Scenario narrative development

The third activity focused on the development of three alternate pathway trajectories based on themes that emerged during community-based scenario planning (see Newman et al, 2023b). Group one explored improving the adaptive capacity of communities, group two focused on the protection and regeneration of ecosystems (including places of cultural and spiritual importance) and group three discussed sustainable settlement planning. Participants were asked to describe what the islands would look like, how different elements interact, and what the day-to-day implications might be. These scenarios considered drivers that were both impactful and uncertain. Scenarios considered short and medium term trends. Narratives were plausible and internally consistent, even when exploring extreme or unlikely futures. Each group had several guiding questions to prompt discussion (see Appendix 3.1).

Land cover change predictions

Once pathway narratives were created, in their working groups participants were asked to reflect on how pathways might influence land use and land cover by 2030. These included predictions of land cover conversions, the possible percentage change, the likelihood of this occurring on a scale of 0 (not possible) to 4 (very likely) and explanations of where such change might occur. Participants were given a range of photographs of land cover types taken from the relevant island and land cover maps for Zanzibar from 2019 as guides. Next, participants were then asked to reflect on how such land use or land cover change might impact livelihood aspects including water, energy, food, health and shelter (health and shelter added by participant request) on a scale from extremely positive to extremely negative for the year 2030.

Land cover modelling

Business as usual scenario

To model land use and land cover changes, baseline temporal scope was defined for 2015 and 2017 and a future prediction for the year 2030. Land cover predictions for the 2030 baseline scenarios were produced using the Land Cover Modeler in the TerrSet Package of IDRISI (v. 18.31). To do these, two land cover maps for the years 2015 and 2017 were used as a baseline reference for change. We used land cover maps obtained from *Copernicus* Global Land Service at a raster resolution of 100 m (Buchman et al, 2020), but modified the classes in accordance with the local community and expert knowledge on the area (see Appendix 3.2). Change analysis was then applied to calculate transitions between land cover types.

Transitions were grouped into four sub models for Unguja and three sub models in Pemba based on the learnt understanding of drivers of land cover change. Within the transition sub model structure, eleven independent spatial variables were included to potentially explain spatial changes in land cover; and included elevation, slope, distance from nearest protected areas, distance from sea, distance from nearest roads, distance from settlements, distance from closed forest, distance from wetlands, distance from built up areas and soil composition. A Boolean layer was used to calculate the relative frequency of pixels which have undergone change, i.e, the evidence likelihood transformation (see Clark labs, 2017). Transitions of less than 250 pixels were excluded from the model to improve model accuracy.

Multi-layer perceptron (MLP) analysis was then performed to calibrate each sub model using dynamic learning rates. MLP analysis predicts the potential of a pixel to transition based on the explanatory power of the selected independent spatial variables MLP then develops a model based on samples of pixels that went through the different transitions shown in the sub model, alongside samples which were eligible for transition but did not change (Civco, 1993; Sangermano et al, 2010). Finally, Markov chain analysis was used to analyse the 2015 and 2017 land cover images and produce a transition probability matrix, transition areas matrix and conditional probability images for the specified future dates (Takada et al, 2010).

Because the transitions to the built-up land class were few between the years 2015 and 2017 it was not possible to adequately model this using the MLP analysis. As settlement expansion and increased tourism infrastructure came up as major themes for land use and land cover change in earlier scoping research it was decided that this needed to be sufficiently reflected in the baseline maps to provide a benchmark of potential change for the years 2030 (Newman et al, 2023). Therefore, transition to built-up land cover was projected separately and added to the BAU land cover maps (see Appendix 3.3-3.5).

Alternative scenario modelling

The next step involved spatially allocating land cover changes for each scenario alternative based on the perceptions, likelihood and location of change identified during workshops. Boolean constraint maps were produced using the Reclass function in TerrSet Package of IDRISI (v. 18.31) using perceptions of predicted land cover transitions. Spatial decision variable maps were created in ArcMap to include specific areas or conditions where change might occur. Additional variables (see Appendix 3.6) that could affect the location of transitions were derived from both previous researches employing scoping focus groups and community-based workshops (Newman et al, 2024; 2023b) as well as wider literature (Suckall et al, 2015; Makame and Kangawale, 2018; Makame and Shacklton, 2019; Dean, 2023).

A fuzzy module was used to convert all the decision variables into factor weights from 0–1. Within the fuzzy module parameters of each variable (i.e. monotonically increasing or decreasing) were specified. Using the Multi Criteria Evaluation module, the weight of influence of each decision variable was calculated based on the authors' understandings of the area.

The Multi-Objective Land Allocation (MOLA) function was then used to select the most spatially viable parcels of land for predicted transitions based on both the Boolean maps and likelihood indicators specified by communities. Within the MOLA function the likelihood of change are area demand predictions specified by stakeholders were applied when calculating the objective weight of each land cover transition. The resultant spatial allocation maps were brought into ArcMap to model land cover for 2030 under each scenario using the conditional function in the spatial analyst toolbox (see Appendix 3.6-3.7).

Maps created though a qualitative process and should be seen as visual representation of different land use and land cover trajectories for supporting water-energy-food security. As such they provide a useful comparative tool for evaluating the potential effectiveness of alternative approaches. The maps are however subjective, more biophysical parameters alongside advanced hydrological modelling would be needed to improve the accuracy of the scenario outputs. Consequently, they should be used in tandem with other approaches to support decision-making.

Results

Past influences on water-energy-food

In both islands there were several interrelated factors which affected water-energy-food security in the last 40 years. Participants detailed events that mediated the wider context in which the nexus operated within, they also made specific links between their perceptions of water-energy-food and the events on their timelines, which are summarised below (Figure 16-19)

In Pemba participants stated that water security increased dramatically with the introduction of electricity as it enabled the pumping of underground water. However, food security was variable due to drought, floods and inflation of imports. Alongside this fuelwood supplies became increasingly degraded due to poor planning for road and building developments, excavation for water and electricity infrastructure, quarries for digging stones to make blocks for new buildings and creation of salt pools. In parallel to this, agriculture, trade, tourism, and urbanisation were seen to increase income and provide alternative routes for attaining water-energy-food security. Formal institutions and legal instruments were also introduced to inform land planning, which was thought to improve the sustainability of land use. However, at the same time, climate change, decreased soil fertility and degradation of the natural environment hindered further growth.

In Unguja participants commented that energy needs changed with the increase in trade and manufacturing, which saw greater electricity provision. They felt that the water supplies had become more modern as people transitioned from well water to piped water through the introduction of new water infrastructure. It was also mentioned that there was a lack of knowledge about water sanitation in the past, and that greater awareness has helped to force improvements. It was recognised that land shortages put pressure on farmers to increase yields, which led to a focus from the government to introduce inputs such as fertilisers and pesticides. Such land shortages also led to land conflicts and deforestation. Environmental degradation was thought to greatly reduce fuelwood supply.

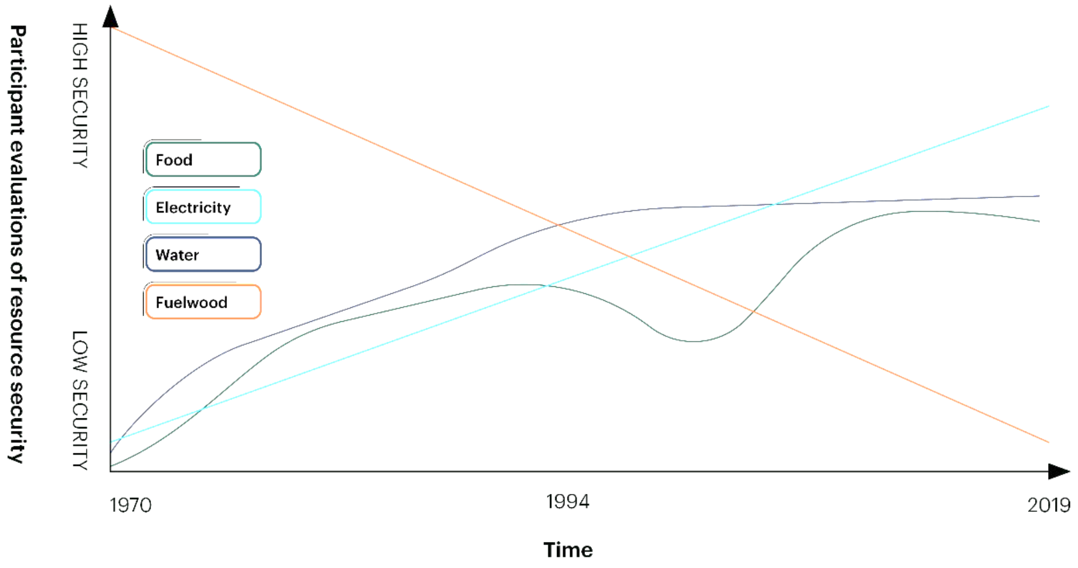

Figure 16. Timeline of events in Pemba which have affected water-energy-food security. The high to low scale demonstrates the participants perception of resource security, with high being high levels of resource security and low meaning very insecure.

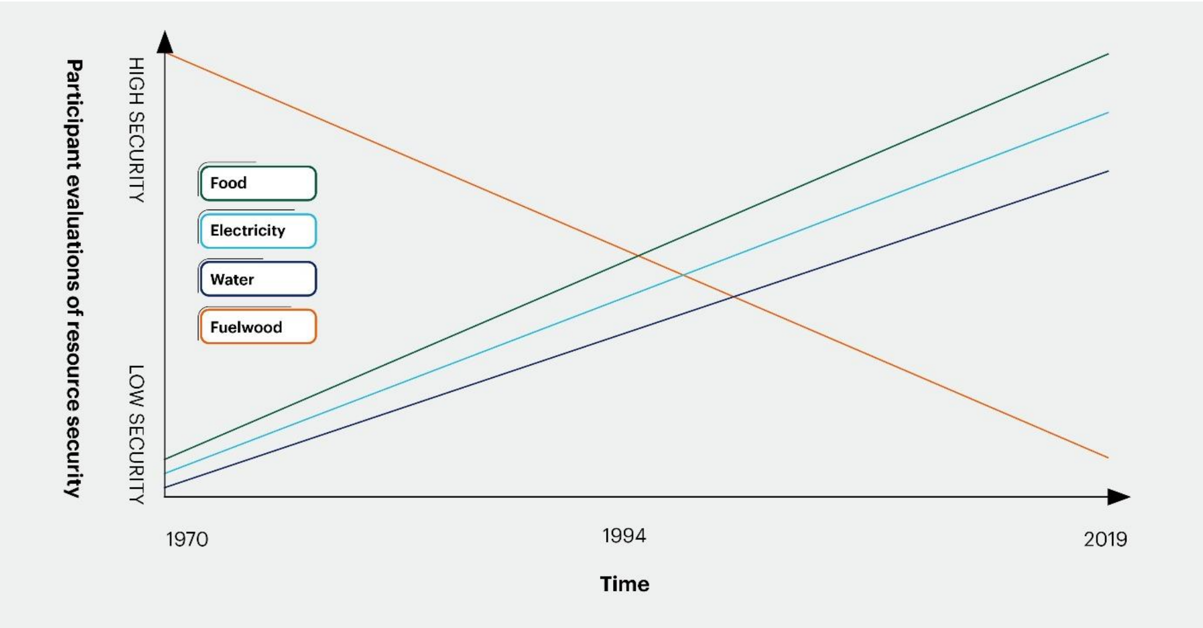

Figure 17. Timeline of events in Unguja that have affected water-energy-food security. The high to low scale demonstrates the participant's perception of resource security, with high being high levels of resource security and low meaning very insecure.

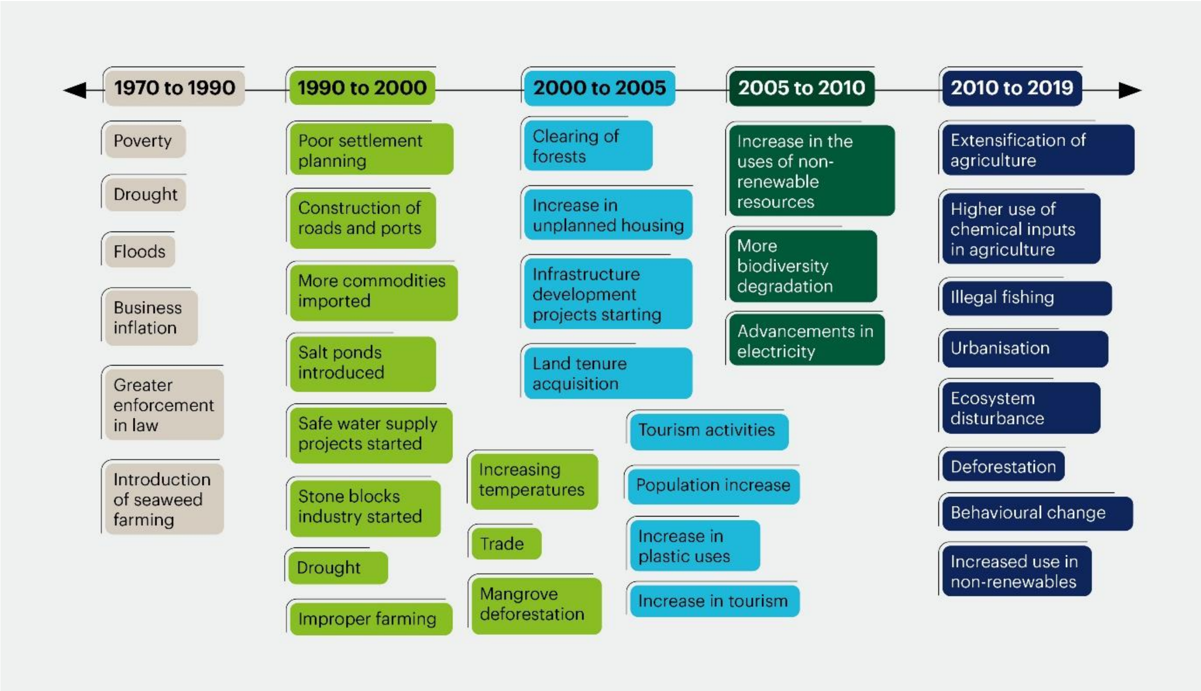

Figure 18. Pemba timeline of events identified by participants which shaped water-energy-food security.

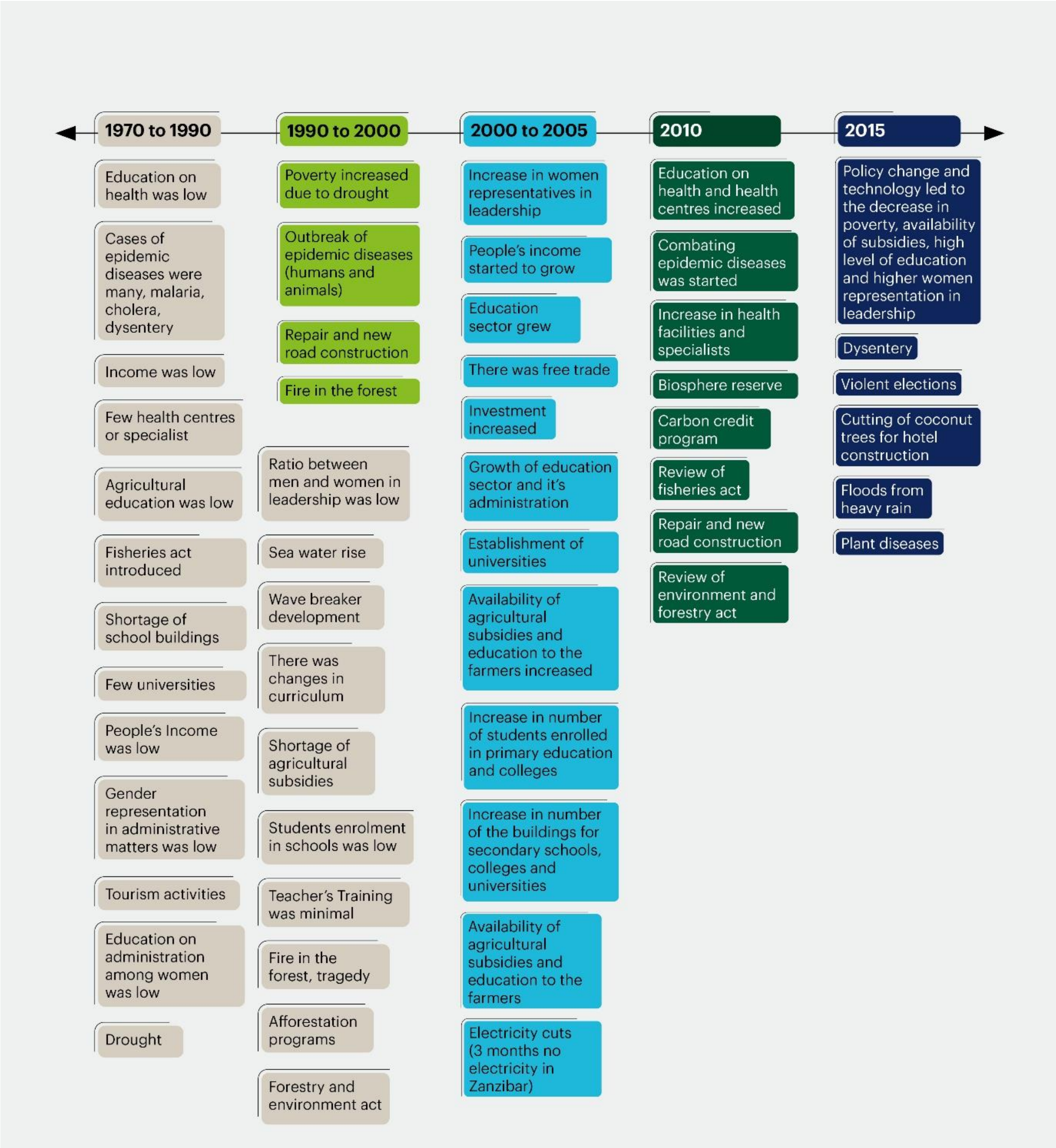

Figure 19. Unguja timeline of events which shaped water-energy-food security identified by participants

Spatial distribution of drivers of change

Three key drivers of change were identified in community-based workshops held before the multi-stakeholder workshops: population increase through both in migration and internal migration, socio-economic development, and climate (Newman et al, 2024). In the community-based workshops, participants were focused on their locality, so to understand these at the island scale participants were asked to code areas of impact, from low to high.

In Pemba, population growth from internal movement and economic migration focused on urban centres, areas with natural capital for tourism, adequate land, productive fishing, or access to the port. Development was expected in areas adjacent to existing urban centres, around the fishing port and in specific sites of greater natural capital which could attract tourism. Climate change impacts were focused in specific coastal areas where flooding events have been witnessed previously. Interestingly stakeholders graded it as medium intensity rather than high due to ongoing mitigation in place, including afforestation of mangrove, construction of seawalls, establishment of community forests, increased awareness, and enforcement of forest regulations (Figure 20).

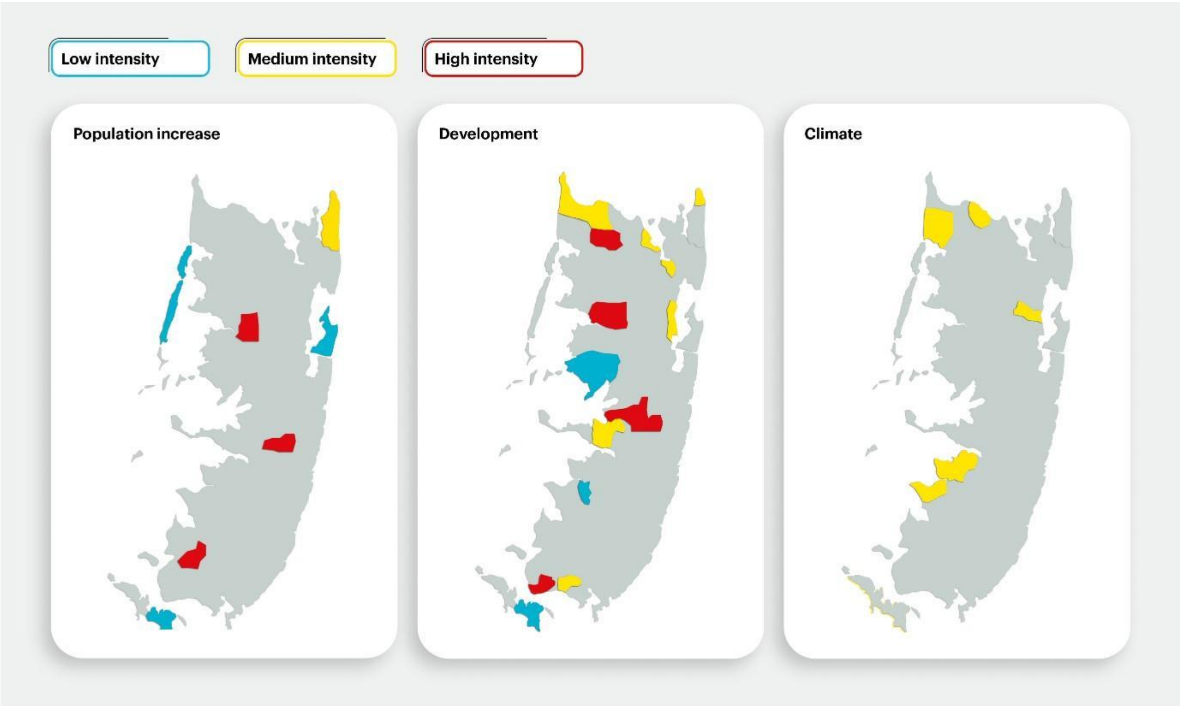

Figure 20. Areas in Pemba where key drivers are most likely to impact water-energy-food security. Population increase refers to internal and in migration, development is associated with socio-economic factors and climate encompasses sea-level rise, severe weather events and climate variability.

Conversely, in Unguja, population increase from economic migration was expected to be more intense in the north and south coastal zones, areas which already experience high levels of tourism. This was thought to extend across the north-west coast, as coastal zones have been steadily developed for tourism infrastructure alongside other development projects. Development on the other hand was predicted to increase mainly on the east coast, in areas with current low levels of tourism, but development projects initiated as part of the Zanzibar Investment Promotion Authority (ZIPA) zones. Unlike Pemba, where climate change impacts were predicted to be quite concentrated in certain places, participants in Unguja expressed concerns for high intensity of pressures associated with wave over wash and salination of water wells across the entire coastal zone, due to deforestation on the coastline and frequent flooding (Figure 21).

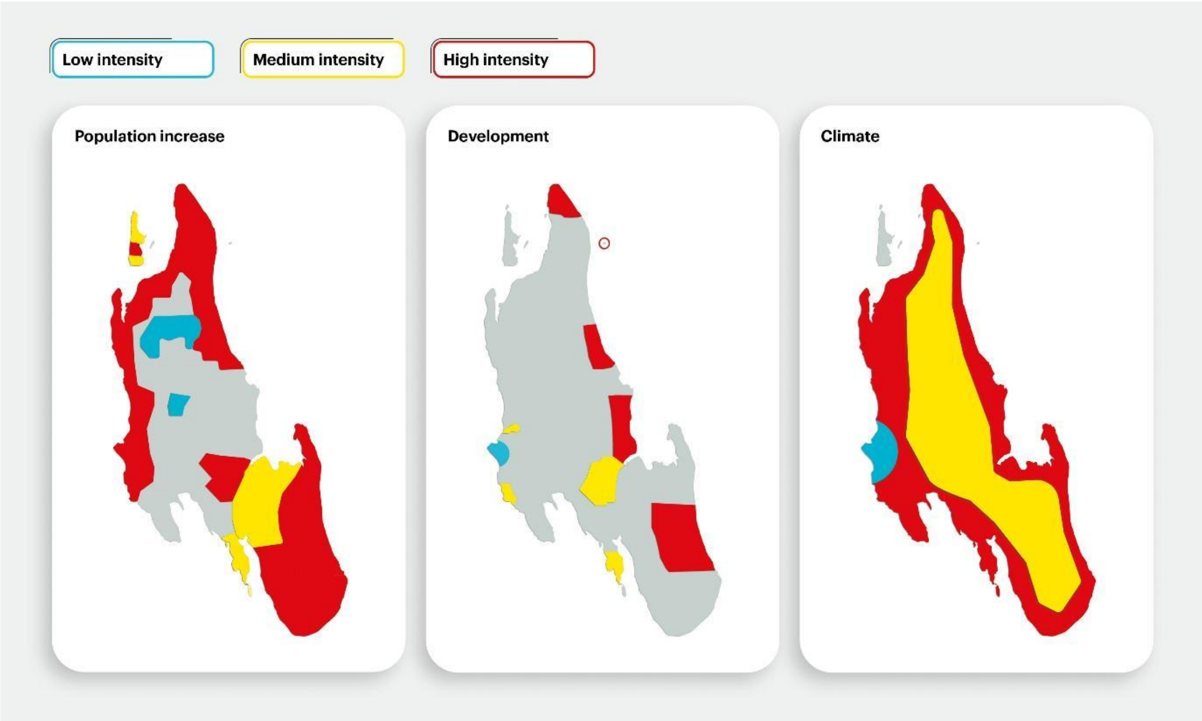

Figure 21. Areas in Unguja key drivers are most likely to impact water-energy-food security. Population increase refers to internal and in migration, development is associated with socio-economic factors and climate encompasses sea-level rise, severe weather events and climate variability.

Alternative scenario narratives

Compared to the Business as Usual (BAU) scenario, there are some interesting commonalities between the three alternate scenarios. For instance, all scenarios recognise that sustainability requires an integrated response, social change, and poverty reduction. Education through continual engagement of communities is seen as important for protecting forests and improving adaptive capacity. In settlement planning scenarios emphasise the need to plan for how economic transitions relating to tourism might socially impact communities (Table 12).

Table 12. Pathway narratives for scenarios based on themes generated from community-based workshops.

Scenario	Narrative Unguja	Narrative Pemba
Adaption	Adaptive capacity is enhanced through education and training across three key areas: entrepreneurship, establishment of cooperative groups and setting up community development projects. Such training recognises how needs change over temporal scales and to explore resource scarcity across spatial scales. This requires a coordinated response from a wide range of stakeholders across government sectors, development organisations and private companies. To support this scenario government bodies would review policies, laws, and guidance.	This scenario builds on existing innovative efforts to provide new ways to get income, encourage entrepreneurship and community environmental education. Existing barriers to adaption are addressed through acknowledgement of the impact of poverty on readiness. Communities and individuals are now empowered to make changes to livelihoods to improve their outcomes. Education for communities is practical and involves multiple stakeholders across government sectors, NGOs, and community-based organisations. Policy between the health, education and agriculture sectors is joined up to support adaptive capacity.
Ecosystem management	Natural forests are protected in small islands, wetlands and areas supporting water reserves, via gazettement involving communities from the beginning. To support this process, policies are put in place that connect land, forests, and fisheries, combined with continual awareness campaigns. Due to poverty and the current dependence on natural forests, efforts are made to ensure access to alternative resources and livelihoods.	This scenario emphasises a multi-stakeholder response to strengthen laws around conservation, environmental education, and suitable land use planning. To conserve nature forests and water bodies, governing bodies have a broad overview of driving factors, such as development activities, population increase, lack of education and poverty. Initiatives are underway to address how entrenched beliefs and traditional practices influence communities' motivation to change.
Settlement planning	This scenario focuses on youth employment, industry, and local investments. A national land use plan is developed which considers, settlement planning guidance, and how economic growth relating to tourism coincides with settlements. This should be developed and supported by a coordinated team across sectors relating to land and settlements. Sanitation is continually improved through better access to cleaning facilities (i.e., waste management, sewage systems and recycling facilities).	Settlements experience substantive changes associated with the growth of industries of agriculture, tourism and extraction of gas and oil. This results in an increased employment, business opportunities, improvements in community services and infrastructure. Spatially, land planning considers these impacts through enforcing the recommendations of environmental impact assessments and encouraging multi story homes to make efficient use of space available. Concurrently, this scenario protects customs, traditions, and norms for people in Zanzibar -to avoid disintegration, security challenges and lifestyles. Cooperation between stakeholders, such as government, institutions, and civil society, is important to navigate the transitions appropriately.

Alternative scenario modelling

Land cover modelling drew out the strong linkages between forests across the water-energy-food nexus. In Pemba, land cover transitions to forested wetland occurred in the coastal fringes. In Unguja, transitions to wetland forest occurred on slow-draining soils further inland. This indicates that transitions to forested wetland are not likely to be associated with reforestation but flooding of existing forest spaces through both coastal flooding and heavy rainfall.

Deforestation is expected across all scenarios, for Pemba, the highest occurrence of deforestation (across natural forests and shrublands) occurred in the *Business as Usual* scenario, followed by *Ecosystem Management, Adaption* and then *Settlement Planning*. Unsurprisingly, the *Ecosystem Management* scenario, which had the lowest expected rates of deforestation, demonstrated the highest perceptions of water-energy-food security for 2030 and was the only scenario which did not reduce permanent waterbody cover.

For Unguja, the highest rates for deforestation were seen in the *Business as Usual* scenario, but this was followed by *Ecosystem Management, Settlement Planning* and then *Adaption*. The *Adaption* scenario also retained the highest amount of permanent waterbody cover. However, in this case water-energy-food security was expected to be greatest in the *Adaption* scenario, which actually showed greatest amounts of deforestation – this could be because adaption scenarios focused on a shift away from forest dependency.

In Pemba, the *Adaptation* and *Ecosystem Management* scenarios included expansion of cropland, whereas *Settlement Planning* involved more plantation forests. In Unguja cropland expansion was not demonstrated in the alternative scenarios, but there was a focus on plantation forest expansion in both the *Ecosystem Management* and *Settlement Planning* scenarios (see Figures 22-25 and Table 13).

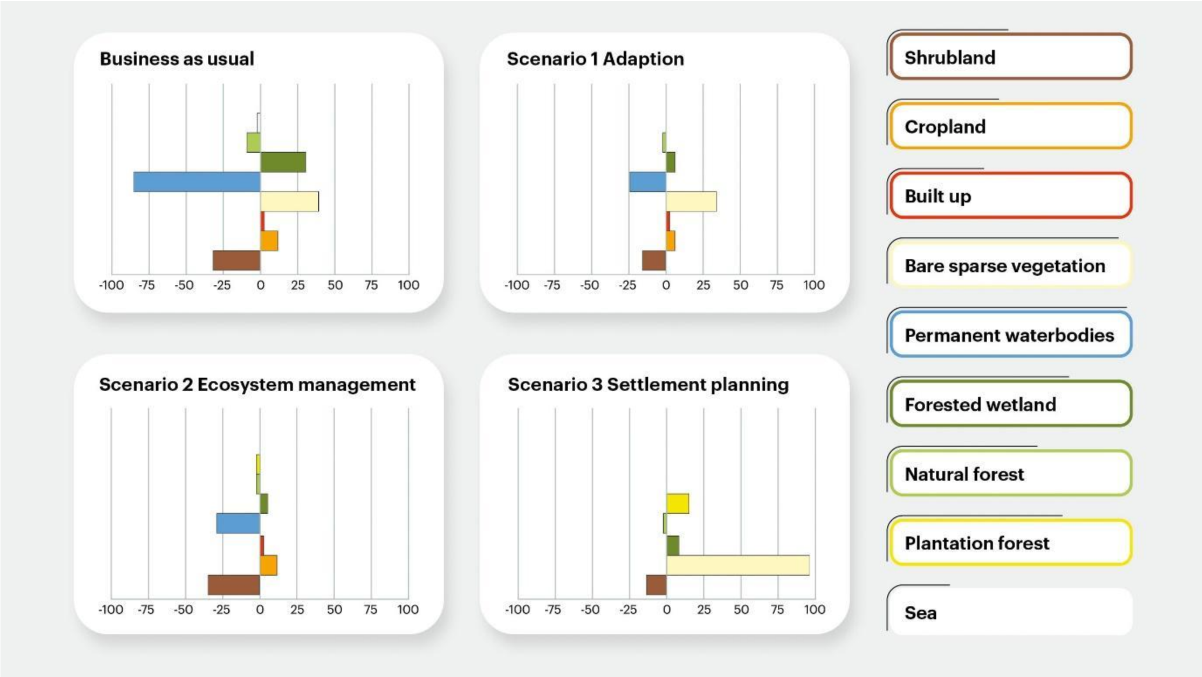

Figure 22. Percentage of land cover change for each land class between present day and 2030 across the four alternate scenarios for Pemba island.

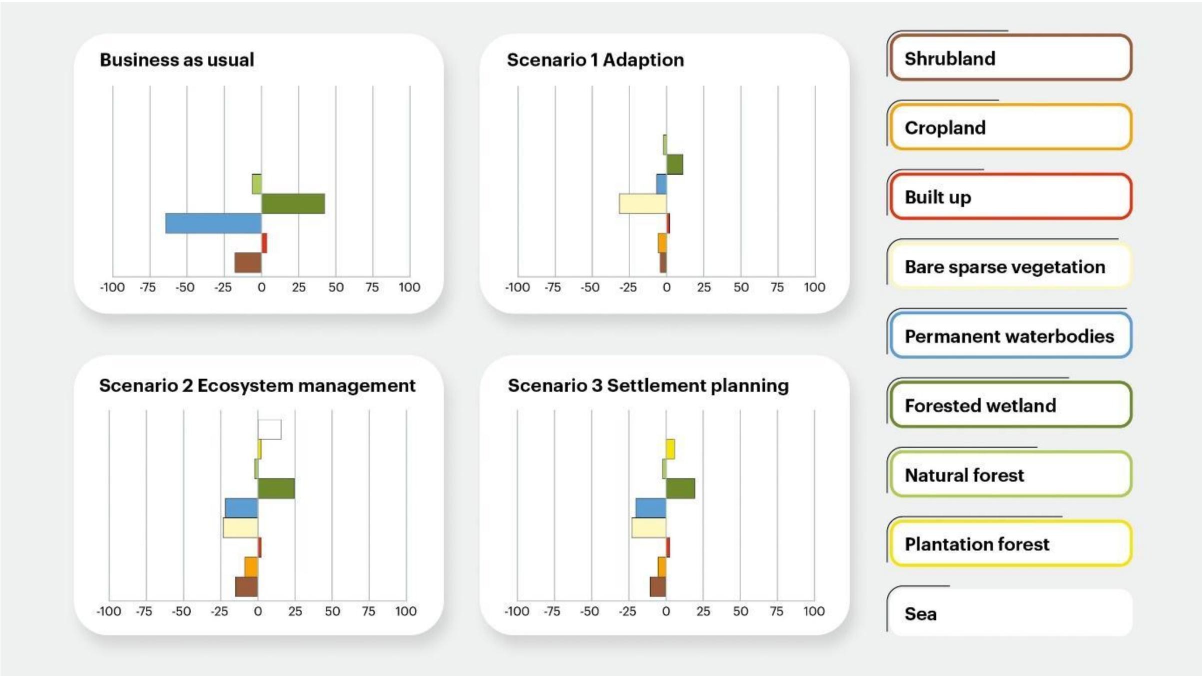

Figure 23. Percentage of land cover change for each land class between present day and 2030 across the four alternate scenarios for Unguja island.

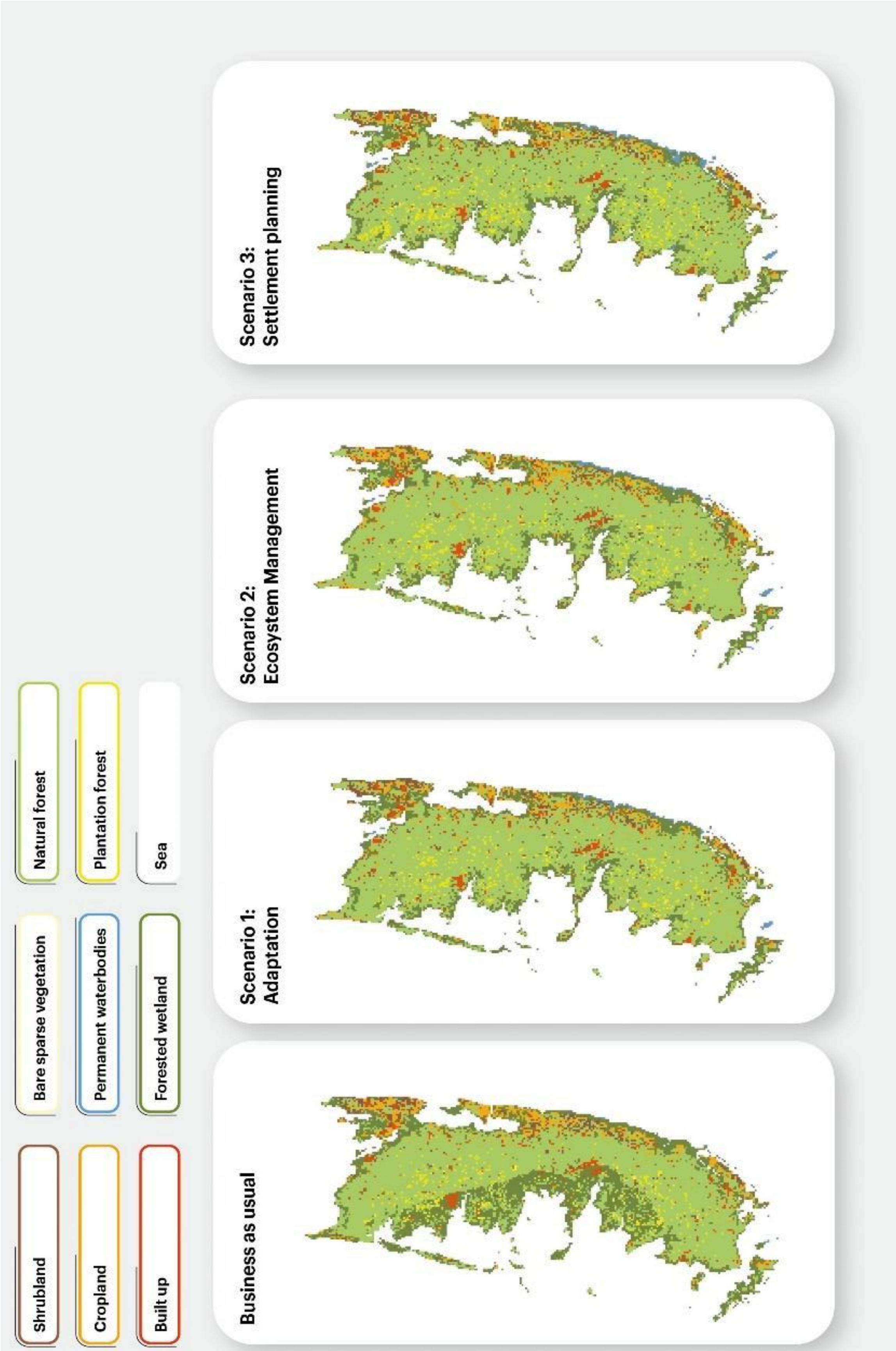

Figure 24. Land cover map products for each of the four 2030 scenarios for Pemba Island.

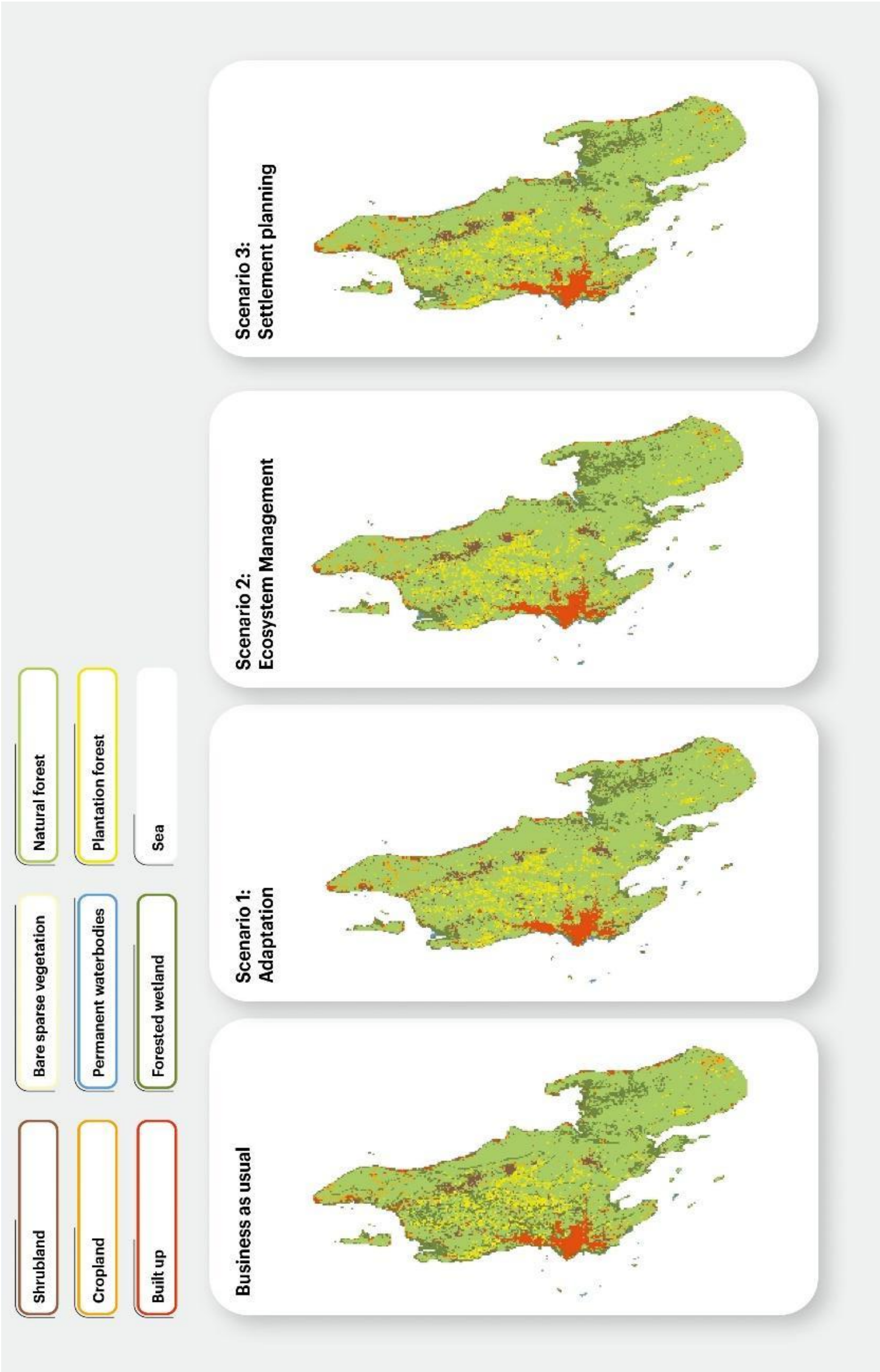

Figure 25. Land cover map products for each of the four 2030 scenarios for Unguja island.

Table 13. Predicted land cover change under each scenario (S1 – Adaption; S2 – Ecosystem management; S3 – Settlement planning).

	Pemba (ha)					Unguja (ha)				
Land classes	2019	BAU	S1	S2	S3	2019	BAU	S1	S2	S3
Shrubland	2.2	1.1	1.6	1.1	1.6	2.5	1.8	2.4	1.9	2.0
Cropland	1.4	1.7	1.5	1.8	1.4	1.1	1.1	1.0	1.0	1.0
Built up	0.8	0.9	0.9	0.8	0.8	2.3	2.4	2.4	2.4	2.4
Bare sparse vegetation	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Permanent water bodies	0.4	0.0	0.2	0.2	0.4	0.4	0.1	0.3	0.2	0.2
Forested wetland	4.8	8.9	5.4	5.4	5.4	3.5	8.4	4.2	5.0	5.0
Natural forest	21.5	17.8	20.9	21.2	20.4	36.3	32.3	35.8	35.4	35.5
Plantation forest	1.0	1.0	1.0	1.0	1.3	3.2	3.2	3.2	3.2	3.1
Sea (gains and losses)	-	0.5	-	-	-	-	-	-	-0.2	-

Overall impacts of scenarios on water-energy-food

Considering overall water-energy-food evaluation for each scenario, the *Settlement Planning* scenario for Pemba came out as the most effective at supporting resource security. In Unguja the overall mean for water-energy-food evaluation were similar, but the *Ecosystem Management* scenario was predicted to support water-energy-food security (Table 14) most effectively. Across nearly all the scenarios, except for the *Adaptation* and *Ecosystem Management* scenario for Unguja, the security of fuelwood supplies was thought to likely reduce. In the workshops, participants predicted that as the use of fuelwood supplies becomes more unsustainable, that they predict that other forms of energy use will increase (predominantly gas). There was a conflict between people wanting to protect forests for the ecosystem benefits, including coastal protection, air quality and soil structure, whilst also meeting their needs for energy, construction, and extraction of other non-wood resources, such as medicinal plants. When evaluating the overall effectiveness of scenarios to meet resource needs, participants felt it was important to consider health and shelter due to the implicit effects resource changes have on these two factors.

Table 14. Evaluation of how each scenario will impact livelihood aspects, starting with water, energy and food, and additional concerns, health and shelter, by request of the participants on a scale of -4, very bad, to 4, very good. P = Pemba and U = Unguja, then S1 - Adaption, S2 - Ecosystem management, S3 - Settlement planning.

	Water	Electricity	Gas	Firewood	Food	Health	Shelter
PS1	1	2	1	-1	1	1	1
PS2	0	0	1	-1	0	1	1
PS3	2	3	1	-1	0	1	1
US1	2	3	3	1	3	3	2
US2	4	3	2	2	3	3	2
US3	4	3	1	-1	3	3	1

DISCUSSION

The *Business as Usual* scenario gives a strong indication that saltwater incursion is likely to increase, as well as flooding of inland spaces where soil composition and land use do not promote adequate infiltration. Alongside this, the spatial analysis shows deforestation and a likely reduction in permanent water bodies. This aligns with previous research, which indicates that small islands in the WIO face serious freshwater shortages resulting from environmental change and deforestation (Comte et al, 2016). These risks are then often compounded by social factors such as inadequate funding for adequate water infrastructure, and inequality of access and rapidity of changes to watersheds and groundwater (Makame and Kangawale, 2018). Although all alternative scenarios envisaged some continued deforestation of natural forests, some were more effective than others for mediating this. As well as pointing out areas of concern, scenarios offer an insight into where cropland expansion or plantation forest could take place, which could strengthen water-energy-food security.

By bringing together diverse stakeholders, scenarios provide more holistic evaluation strategies to secure water-energy-food into the future (Kariuki et al, 2022). While no one scenario offered an ideal set of solutions for addressing environmental challenges and meeting water-energy-food security, several cross-cutting themes for future planning that support resource security became apparent. These included integrated approaches for managing environmental change, community participation in decision-making, effective protection of forests, cultural sensitivity to settlement planning and development and poverty alleviation. Because of these emergent alignments, this discussion will focus on examining how scenarios could support strategic action towards water-energy-food security and more broadly the 17 Sustainable Development Goals. Although the scenarios did not explore beyond the 2050 time horizon, they offer insights which can contribute to the achievement of Zanzibar's Development Vision for 2050 towards their 2030 targets (ZPA,

2020) and wider agendas for sustainable land management such as the African Agenda for 2063 (DeGhetto et al, 2016).

Integrated planning across sectors

Within workshops, participants emphasised the value of a cross-cutting nexus government approach which explicitly facilitates cross linking between water-energy-food issues. This aligns with recommendations from the most recent SDG progress report, which state that "*epistemic communities need to reflect the diversity of society, and their interactions will need to be far more multi-directional and multi-disciplinary, so they can effectively address complex and interlinked challenges and goals"* (Global Sustainable Development Report, 2023: 91). Zanzibar's 2050 Development Vision also sets out to develop linkages across all sectors (ZPA, 2020). More generally, wider research states that an integrated approach for water-energy-food is seen as essential for future security (Daher & Mohtar, 2017). Efforts should therefore pay attention to how meaningful collaboration happens.

Supporting collaborative practices across sectors might require the designation of specific roles to be responsible for identifying overlapping areas of interest where different groups might be able to contribute in a more integrative way (Oborn and Dawson, 2010). Resourcing aimed at cross sector working groups might also be needed to stimulate more coherent action. Further to this, multi- and trans-disciplinary action requires critical reflections on power distribution and accountabilities (Comeau-Vallée & Langley, 2019). Consequently, reflexivity is needed to surface participants' positionality (including their values and beliefs) and challenge underlying assumptions and power relations (Bilella et al, 2023; Gates et al, 2023). This can not only provide a more accurate and nuanced understanding of the impacts of actions undertaken, but also avoid a culture of silence where fundamental issues remain unresolved (Fetterman, 2017).

Community participation in decision making

Participants advocated for participation in decision making. Integrating bottom-up experiences of all segments of populations and subnational identities into policy decision making has been shown to result in tangible synergistic solutions that are actionable (Pereira et al, 2021) and key for the delivery of the SDGs (Global Sustainable Development Report, 2023). Though vertical dialogues connecting experience to policy are often limited (Pittore & Debons, 2023). Moreover, whilst community level insights are often acknowledged as important to developing a holistic understanding of complex issues, they are not drawn upon directly but through advocates such as NGOs, as in the case in the development of Zanzibar's 2050 vision (ZPA, 2020).This said, there is movement towards people focused processes for development, for example, the Africa 2063 vision outlines key stakeholder groups for consultation, including women and youth (DeGhetto et al, 2016).

Specific to this research focus, there is an increasing awareness that social-ecological understandings for water-energy-food systems are missing in nexus analysis, which risks inadequate management (Yung et al, 2019; Hibbett et al, 2020). But for effective elicitation, attention needs to be given to what prevents effective participation (Cleaver, 1999; Cleaver, 2005; Gustavsson et al, 2014 and Brown and Kyttä, 2018). For instance, communities may lack trust in authorities due to past experiences of exploitation or broken promises. This mistrust can lead to reluctance in participating in new initiatives (Massarella et al, 2018). Self-esteem, capacity, gender dynamics and differences in education can also impact the dynamics and communication in participatory methods (Gustavsson et al, 2014).

In this study preparatory work was carried out at the community scale to inform the framing of the multistakeholder workshops to try to recognise different agencies. Nonetheless, there were barriers to participation in the multi-stakeholder workshops that still existed, which could have influenced the results. These were centred around differences in literacy and education, which affected people's confidence. Facilitators were aware and mediated these challenges through supportive discussion and confidence building around the value of insights from community perspectives. But this observation serves as a reminder that there can still be an imbalance of representation of community voices even when they are represented in multi-stakeholder workshops.

Centralising community needs in planning

Findings revealed a need for more consideration of diverse needs to design the most effective use of the space. Whilst there is an acknowledgement of unplanned settlements and challenges regarding poor sanitation and energy infrastructure, plans in Zanzibar's 2050 Vision do not yet explicitly address this, especially in rural areas. At present, there is a limited understanding of how the built environment impacts the water-energy-food nexus (Heard et al, 2017). Houses in the rural settlements are mostly built without formal planning, and socially constructed in relation to how people organise their lives (Myers, 2010). More interrogation is needed to explore how the current nature of settlements align with opportunities for strengthening water-energy-food security, but also how they might constrain it.

What also came through within the research process was the concern that participants had about development trajectories in terms of their suitability with social values and livelihoods. There was a strong advocation for settlements to have a degree of separation from tourism centres. Given that tourism is a vital part of Zanzibar's economy, it is essential to implement sustainable tourism practices that do not adversely affect the vital ecosystems, or cultural heritage which local communities value (De Jong Cleyndert et al, 2021; Baloch et al, 2023). At present, the benefits of tourism do not get distributed amongst the local communities. Conversely, they have seen a reduction in quality and availability, increases in the price of locally caught fish and conflicts with coastal zone use (De Jong Cleyndert et al., 2021; Makame et al., 2015; Lange, 2015).

Looking forwards there are also several considerations that need to be made to improve community resilience to outlined drivers. Improved drainage systems, erosion control measures, and constructing infrastructure that is resilient to climate change impacts, will be key in adapting to and mitigating the impacts of environmental changes (Thorn et al, 2021c). Building guidelines should be revised to encourage the construction of energy-efficient buildings, incorporating renewable energy sources such as solar and wind power, thereby reducing dependency on non-renewable energy and forest products. Green infrastructure spaces and rain gardens could also aid in water management, improve water, and air quality, provide local space for food production, and mitigate urban heat island effects (Thorn et al, 2021a).

Protection of remaining forests

Scenario narratives advocated for more regulation and protection of forests, especially those which play a critical role in protecting coastlines from sea level rise and the increased frequency of severe storms (Chunga, 2023). Key elements in this regard include restoring natural barriers like mangroves, which can help protect against erosion and flooding, as well as creating buffer zones and regulating coastal development and construction away from high water marks (Monga et al, 2022; Nyangoko et al, 2022). Awareness campaigns and education around certain themes such as deforestation was highlighted as central to aligning communities to land use policies. For instance, previous research in Zanzibar found that education around the ecological links between mangrove ecosystems and resources such as fish were key to obtaining management support (Shunula, 2022).

Concurrently, it was recognised that alternative energy provision interventions are needed so that people are not adversely affected by restricted access to forest resources, which they depend on for energy needs (Okello et al, 2019). As part of the Zanzibar Vision for 2050, there is a focus on extracting offshore oil and gas, which has tensions with international goals for reducing the use of fossil fuels (UNFCCC, 2023). Transitioning to gas usage for cooking depends upon capacity to afford this as a fuel source.

There are broader links to energy that need to be considered within energy security transitions. Zanzibar's strong dependence on mainland Tanzania remains a constraint to development as demand is expected to exceed cable capacity within the next few years due to the introduction of new hotels (Dean, 2023). Lack of energy results in frequent power cuts and challenges with water extraction and supply. There is also a constant tension between Zanzibar and TANESCO (Tanzania's electrical provider) because of excessive unpaid electricity bills, resulting in threats to cut off power supply (Dean, 2023). This would have extreme negative implications for the provision of water, which depends upon electricity for pumping.

Renewable energy has some capacity to reshape energy relationships and enhance resilience. For instance, ZAWA (Zanzibar's water authority) has begun installing solar water pumps (Dean, 2023). Solar has also been found a more feasible alternative to households who cannot afford to connect their homes to the national grid. When this research was conducted, connection costs were variable and the onus for expanding electric infrastructure was placed on the user. Since then, ZENCO (Zanzibar's electricity provided) announced a flat rate of 200,000 TSH (around 85 USD). Whilst this is a fairer approach, it is still out of reach to many citizens. As a result, solar remains a more viable option, especially to those without land tenure.

Poverty alleviation

Communities further sought to harness opportunities to strengthen their livelihoods outcomes and in turn water-energy-food security. There was a call for more support for entrepreneurship, which could also see Zanzibari's connect to tourism related opportunities. There was a demand for adopting more innovation, for instance in the farming sector. Community development together with education is also seen as important for stimulating skills and broadening opportunities out from urban to rural communities. Further to this, there were ideas around how communities could organise themselves to develop cooperatives, which might stimulate funding streams for development activities. Zanzibar's Development Plan for 2050 has a strong focus on diverse income opportunities, and seeks to stimulate opportunities across agriculture, finance, trade, tourism, blue economy, creative and digital and oil and gas sectors (ZPA, 2020). It also seeks to create better linkages between tourism and local produce as well as support training to increase people's capabilities to enter the workforce (ZPA, 2020).

Limitations

There are some limitations which need to be recognised. Firstly, the *Business as Usual* scenario modelling used land cover maps over a close time series to project land cover changes for the future. It would be more suitable to analyse changes over a longer time interval, but this was not available at the time of analysis. The *Business as Usual* map alongside the alternative scenario maps should not be interpreted as accurate representations of the future, but as comparative visuals of alternative approaches for managing drivers of change into the future to guide decision making. Secondly, whilst there was a concerted effort to bring together diverse stakeholders, it is worth considering who was not involved. For instance, migratory groups from the Masai Mara periodically travel to and from Zanzibar during high tourism season for work. They interact with landscape to meet their needs and therefore have an influence on the nexus – but were not included in visioning for the future. Similarly, international migrants who have settled in Zanzibar were not involved, but often have an impact on land cover through building or tourism related business. Moreover, while efforts were made to reduce bias for the sampling of participants by setting out specific guidance for the recruitment, there is some likely bias evident in the results in using village leaders as gatekeepers. For instance, over representation of the current political party. Finally, ideally all stakeholders should have had the opportunity to give feedback on the results and further modify the land cover maps. In this case it was not possible due to the global pandemic in 2020.

Future considerations

Though the research process was able to draw out planning approaches that could support water-energy-food security through the mediation of drivers of change, there was no one set of solutions that completely addressed resource challenges and deforestation was still expected to occur to some extent across all the scenarios modelled. Although scenarios can be useful for working with the uncertainties of the future and challenging assumptions behind current societal patterns, they are limited in that they do not necessarily provide strategies for action, express what people *want* to see in the future rather than what is only plausible or envisage futures that are sufficiently different from the present to encourage transformative rather than marginal or incremental change (Sharpe et al, 2016). Having a longer time horizon could help participants to explore more ambitious interventions, but at the same time it means working with greater uncertainty. Future research could valuably employ more ‘pathways’-type futures approach such as Three Horizons, working with local participants to collectively envision their desired futures and creatively identify necessary actions for supporting transformation (Collste et al, 2023).

There was also a lack of consideration towards global influences when exploring water-energy-food security to local land use. Communities in small islands are net importers of food and therefore highly exposed to food price spikes (Connell et al, 2019). While subsistence farming continues to be an important aspect of meeting food needs, climate change, land use competition and poor soil fertility all contribute to reduced yield (Paddock and Smith, 2018). So, whilst results are useful for building a picture of place-based water-energy-food security understandings, there is a need to capture global influences and their impacts across these more local scales. This might be achieved by involving trade, geopolitical and global conservation experts into the workshop dialogues.

Further work is also needed to explore the wider implications of informal migrant settlements, and the social-ecological interactions of migrations within the water-energy-food nexus. Unplanned urban sprawl from both local populations and migrant settlements can lead to expansions into natural environments or agricultural land, as in the case of Chuini Zanzibar (Suomela, 2019). Social-ecological relationships underpinning water-energy-food security might be especially precarious for migrant populations because of land tenure insecurity. For instance, those renting property or land can be more reluctant to invest in infrastructure such as electricity because they could be forced to move (Dean, 2023). Therefore, what might be happening is a divergent set of social-ecological relationships for migrant populations compared with Zanzibari communities. These need to be understood so that they can be captured in future scenarios.

CONCLUSION

As communities in small islands within the Western Indian Ocean have strong social-ecological relationships within the water-energy-food nexus, they are well-positioned to explain the implications of different types of pressures and how this mediates these relationships. This study provides an example of how community insights can be integrated with knowledge from formal sectors to evaluate the impact of alternative interventions more effectively. Findings reveal important understandings with regards to where drivers of change might most impact water-energy-food security and offer socially acceptable interventions to mediate such.

Results could inform near term land use planning that can enhance climate-resilient rural livelihoods, better conservation outcomes and sustainable tourism development. Specific policy recommendations arising from this work include: (1) focusing conservation and forest regeneration efforts around areas predicting a loss in permanent water bodies; (2) working with communities and hoteliers to reforest coastlines to provide protective buffers against storm surges at a landscape scale; (3) invest in solar infrastructure for water pumps to limit disruptions in supply caused power outages; (4) actively support the establishment of woodlots for producing fuelwood at scale on land not suitable for food production, whilst also investing in long term sustainable energy transitions; (5) a focus on local enterprise and the development of skills to harness emergent opportunities; (6) enhance adaptive capacity of communities through training in innovative agricultural methods.

As well as more specific policy outcomes, the results from the paper also advise on processes for how policy decisions should arise, with community involvement and integration between sectors being key. Enhanced participation from communities at the onset of landscape planning was thought to provide a better opportunity for protecting community values and culture. Productive discourse and co-development of strategic action involving relevant organisations were thought to be important for increasing Zanzibar's capacity to support better water-energy-food outcomes.

Understandings from communities and experts about social-ecological interactions within the water-energy-food nexus also indicate that scenario alternatives would operate differently for the different islands, demonstrating the importance of understanding the social, environmental, and economic contexts and how they might connect to national policies.

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5 CONCLUDING DISCUSSION

The thesis makes several contributions to towards understanding of social-ecological interactions within the water-energy-food nexus for a small island context. In addition to this, it provides an example of how this type of understanding can be applied to scenarios development aimed to influence both local to regional action and national policy.

Key contributions are detailed below:

EMPIRICAL UNDERSTANDING OF WATER-ENERGY-FOOD SECURITY IN A SMALL ISLAND CONTEXT

Findings from the scoping study, presented in chapter 2, indicated that challenges with water and electricity infrastructure, increasing intensity of land use, climate change and deforestation causes shocks and stresses that ultimately impact resource security. Impacts include harvest loss, acute disruptions in water provision alongside overall degradation in the quality of well water and depletion of fuelwood resources. Findings demonstrated that spatial characteristics mediate the scale at which communities experienced shocks and stresses. For instance coastal areas with high levels of deforestation experienced greater negative effects from storm surges, areas with more commercial agriculture had more land use competition and deforestation, and remote areas typically were less connected to service infrastructure. Findings add more depth to our understanding of resource security in small islands as they capture insights from less researched areas, such as inland and peri-urban spaces. This understanding of temporal and spatial complexity at landscape scales creates an opportunity to target actions towards reduced insecurity to specific areas, whilst also considering temporality and appropriate timescales. Whilst wider literature increasing advocates for a landscape approach to exploring sustainable livelihoods (ie. Biggs, 2018; Wu, 2021), findings in chapter 2 provide empirical evidence which emphasise the importance of understanding and planning for temporal variability in pressures.

Findings from community-based workshops, presented in chapter 3, uncovered connections that communities made between land use and land cover change and resource security in greater depth. Challenges around deforestation and fuelwood security were shown to be of most concern. Participants explained that because of the extent of deforestation in community forests, people were extracting fuelwood from protected mangroves and plantations. They saw a relationship between reductions in forest cover and lower river levels as well as the drying of oases, and spoke about challenges of keeping livestock as there was less available shade. A reduction in forests and biodiversity, alongside climate change effects was also linked to reductions in soil fertility and increased outbreaks in pests and diseases. One of the most striking changes demonstrated in land cover change map drawings was in the introduction and expansion of built infrastructure, including roads, hospitals, and schools, alongside water pipes and electricity connections. Whilst this was regarded positively, participants recognised the extent of forest loss associated with this and reflected on the loss of *"very old and famous trees"*. Habitat fragmentation and biodiversity loss is an ongoing concern in small developing islands (Steibl et al., 2021; Fernández-Palacios et al., 2021); especially in relation to vegetation loss in coastal extents given the increasing risks associated with storm surges (Suyadi et al., 2021). Whilst research in small island demonstrates an acute awareness of coastal vulnerability to storm surges and sea level rise (Mycoo et al., 2022), results from both chapter 2 and chapter 3 indicate the need to explore ecosystem management for water security in areas experiencing forest loss further inland.

Results from chapter 3 presented significant drivers connected to land use change that posed challenges for water-energy-food security, as well as site specific nuances. Participants indicated that climate change, socioeconomic development and population increase are of national significance when considering water-energy-food security. They also shared that in coastal areas, tourism was something to be more specifically focused on. Wider research as indicated that tourism contributes to deforestation (Käyhkö et al., 2011), overextraction of water (Slade, 2012) and reduced access to protein, especially fish (Makame et al., 2015). There is also a growing body of research which is detailing resource challenges arising from climate change (Adger et al., 2009; Duvat et al, 2020; Crisman & Winters, 2023). However, local population dynamics are not captured well in wider research into land cover change in small islands. Here, we understand that both internal migration and external migration have implications for resource management at the community level. For instance inland spaces with higher agricultural potential have stimulated in migration and put additional pressure on forest stands. Moreover, external migration of young men into income generating roles has seen a decrease in subsistence farming as key livelihood activity.

Finding across chapter 2, 3 and 4 show that forests are integral to the water-energy-food nexus, for extraction of fuelwood, groundwater retention and soil quality. They show that fuelwood security is a key challenge considering its scarcity alongside the limitations for transitioning to other energy types. Overextraction of fuelwood has been recognised as a key driver of deforestation for decades, and whilst reduced extraction has been advocated for, there have been no meaningful routes to alternatives in many cases (Benjaminsen & Kaarhus, 2018; Jape & Najar, 2024). Discussions with communities revealed that as local forests become depleted, there is increased pressure on existing forests, but also, more people are turning towards buying fuelwood as charcoal from areas with greater forest cover – therefore accelerating deforestation in remaining forest stands. Findings from chapter 3 show that both individuals and communities are establishing woodlots to sell fuelwood, this is replacing areas previously farmed for food.

Results from multistakeholder scenarios workshops, presented in chapter 4, show spatial patterns of how previously identified drivers of population increase, socioeconomic development and climate change might be experienced across each island. This demonstrated distinctly different patterns in how population increase, and socioeconomic development would include land cover, with coastlines being the most affected in Unguja and urban centres in Pemba. Population distribution is an important factor when considering vulnerability to climate change, to determine levels of exposure to risk and how to what extent flooding or drought might impact communities (Scandurra et al., 2018). Perceptions of climate change impacts were also quite different, while they were focused on coastlines for both islands, participants in Pemba islands imagined less severe effects. This potentially connects to increased pressures on natural resources occurring in Unguja island due to increased degradation of natural resources from tourism. By identifying potential areas of increased vulnerability to climate change, the research responds to the IPCC's call for mapping areas of vulnerability and resilience (IPCC, 2022). This type of detailed mapping show how drivers are experienced over heterogeneous landscapes; this emphasises the value of bringing diverse stakeholders together to deliberate and form an integrated understanding of change. The outputs from this exercise are valuable for informing Zanzibar's Vision for 2050. They also show that drivers and pressures are contextualised according to place and that small island experiences of drivers can materialise in different ways.

In chapter 4, three scenario narratives were also presented. Scenario themes were co-created by multiple stakeholders on each island, centred on the previously identified themes of *Adaptation*, *Ecosystem Management* and *Settlement Planning* – which arose through discussions in the community based workshops presented in chapter 3. In the *Adaptation* scenario for Unguja, participants identified entrepreneurship, establishment of cooperative groups and setting up community development projects as key. This was mirrored in Pemba, but with the addition of practical education which supported more sustainable environmental stewardship. The *Ecosystem Management* scenario across both islands were also well aligned, and had a focus on addressing drivers of deforestation and strengthening the protection of forests through integrated policy across sectors. The *Settlement Planning* scenario emphasized the importance of integrated planning, especially in relation to balancing the needs of socioeconomic activities with communities, but in Unguja participants also discussed balancing the cultural needs and values of the community with tourism.

The scenarios outlined encompassed social-ecological concepts and explored relationships between livelihoods and landscapes. Whilst the three alternatives were seen as separate trajectories, there were cross-cutting themes in the approach to realising each scenario. These included integrated planning across sectors, meaningful community participation in decision-making and centralising community needs in planning. Consequently, scenarios offer both insights into future actions which they believe could address their water-energy-food challenges and how meaningful planning towards sustainability could be achieved through collaboration with communities. This adds support to the many studies that recognise the benefits of meaningful community involvement (Brown & Kyttä, 2018; Gustavsson et al., 2014; Plenan et al.,2020). This study also shows that deliberative discussion between communities and key stakeholders can uncover the key shifts needed in governance to strengthen approaches for attaining water-energy-food security.

While the narratives demonstrated many similarities, land cover modelling indicated that the way they might potentially influence land use and land cover across the islands differed. In Pemba, cropland cover differed between scenarios, with more cover shown in the *Business as Usual* scenario and *Ecosystem Management* scenario and less the *Adaption* and *Settlement Planning* scenarios. Whereas, in Unguja, cropland cover remained stable across all scenario options. In Pemba, permanent waterbody loss was less in the *Settlement Planning* scenario, whereas for Unguja it was the *Adaption* scenario that mediated waterbody loss most effectively. This is an especially useful finding given the lack of research around climate change impacts on freshwater in small islands (IPCC, 2022). Natural forest loss was expected to some extent across all scenarios for both islands, in Pemba the *Ecosystem Management* scenario most effectively retained forest, for Unguja the *Adaption* scenario retained slightly more. As a result, the *Settlement Planning* scenario was identified as the most effective at supporting resource security in Pemba and the *Ecosystem Management* scenario in Unguja. Findings support the idea that actions towards achieving a certain aim need to be contextualised and locally appropriate to respond to place specific challenges and opportunities (Oteros-Rozas et al., 2015; Blazan et al., 2018; Berthet et al., 2022). They further demonstrate that communities, together with key stakeholders, can effectively co-create locally appropriate pathways for strengthening water-energy-food security. Creating capacity for this type of integrative decision-making could be hugely beneficial for ensuring progress towards commitments such as the SDG’s.

Conceptual contribution of a social-ecological focus for nexus approaches

Despite the water-energy-food nexus approach being identified as highly important for addressing resource challenges at the onset of this project (Miralles-Wilhelm, 2014: Biggs et al., 2015; Albrecht et al., 2018), there are still only a few studies who have adopted it to explore sustainability on small islands (Winters & Crisman, 2023; Martin del Campo et al., 2023). To date, this body of research is the only known example of using a social-ecological framing at the community level for exploring the nexus in a small island context. This said, there is a move towards exploring interactions across a nexus and some examples of this through a human lens. For instance Dean (2023) explored the water-energy-land nexus in Zanzibar, finding that decisions around energy infrastructure and transitions must somehow balance energy justice, environmental conservation, livelihood security, land tenure and international tourism. Interestingly, through an ethnographic approach which drew upon trusting long standing relationships, Dean (2023) was able to uncover some of the political tensions around water, energy and land, finding that dependence on mainland Tanzania for energy through under water cables was politically uncomfortable. Winters and Crismans (2023) and Martin del Campo (2023) also explore the nexus in small islands in the Caribbean, with special consideration to risk management and governance. This emergent focus on exploring resources using a nexus approach in small island contexts at multiple scales is interesting and demonstrates it potential to inform hazard management as well as sustainability transitions. This study provides a valuable contribution by showing how a social-ecological conceptualisation of the water-energy-food nexus can uncover more contextualised complexities, and capture temporal variances often missing in nexus research.

This framing of water-energy-food security helped to better understand local social-ecological relationships in many ways. In the scoping stage detailed in chapter 2, it unveils the differential pressures people experience both spatially and temporally. As previously mentioned, remoteness coincided with a lack of resource infrastructure, areas with higher levels of commercial agriculture experiences increased levels of deforestation and land use competition, whereas areas with natural capital, such as Pete adjacent to Jozani forest harnessed opportunities related to ecotourism through conservation. At the same time it helps to show that protected forests are being increasingly degraded as fuelwood supplies across the islands are becoming depleted. The nexus framing further showed that resource insecurity challenges increase in dry season, as low rainfall meant less recharge of water and limited supply for watering crops, but also increased water extraction from the tourism industry. Exploring these issues through a nexus approach gives a greater sense of how changes in the landscape affect people's resource security in multiple ways.

The conceptual framework developed at the start of the thesis in chapter one described water-energy-food security as the key components for environmental livelihood security (ELS), this evolved throughout its application. During the field work process, it became clear that environmental livelihood security is more complex than this. Communities raised health and shelter as other important dimensions during focus groups and community based workshops. In the Kesho workshops, political and cultural dimensions were also found to be key influential factors shaping environments and livelihoods. Consequently, it appeared to be more appropriate to use the language of 'water-energy-food security' in place of 'environmental livelihood security' throughout the data chapters. In the scoping study it was intended that the results about how people respond to shocks and stresses would be organised into the themes of stability, robustness, durability and resilience. However, many of the responses pointed towards coping strategies of maladaptation. As such results were analysed more broadly to show responses to change and the levers and barriers to this. In the Kesho scenario workshops, there was an emphasis on how to prepare to cope with known stresses in a proactive way – assuming that being proactive was preferable. Considering the impacts of Covid-19, an unforeseen shock, it has become apparent that having capacity to react ex-post is also highly important for managing resource security. Consequently, having been through the fieldwork process, the central theme of the framing shifted from environmental livelihood security – to water-energy-food security. Space was created in the framework to capture responses to change that are maladaptive. Moving forward, future applications of the framework could place greater emphasis on increasing capabilities for responding to unknown change ex-post, as well as more proactive preventative approaches.

METHODOLOGICAL CONTRIBUTION OF COMMUNITY CENTRED KESHO APPROACHES

By talking to communities in depth about their experience of shocks and stresses for resource security, results also better convey variances in impacts. For instance in chapter 2, results showed that piped water supply is consistent in some areas, meaning people can reliably collect water closer to home regularly, whereas in others its less regular or more sporadic – which can lead to more time spent gathering water. Finding also brought up breakdowns in supply due to maintenance issues which can go unresolved for lengthily periods of time, meaning people revert to unsafe drinking water. These nuances could be masked when looking at overall trends in water-energy-food security over time i.e., the presentation of perceptions in Figure's 16 and 17 of chapter 4. This demonstrates the value of having more in depth discussions which allow for detail to be drawn out. This adds support to the idea that qualitative focus groups can contribute social-ecological research, through uncovering options, attitudes and perspectives that give meaningful information (Tùmen Akyildiz, 2021); but critically, chapter 2 highlights the importance of exploring the temporally of pressures when engaging in focus group discussions.

The ability to be able to explore change and its implications for the water-energy-food nexus over different land cover types across two islands with alternative socioeconomic trajectories was extremely valuable. In community-based workshops detailed in chapter 3, key drivers for change for informing policy at a national scale were identified, these included population increase, socioeconomic development, and climate change. But what we see in chapter 4 is that these operate across different spatial scales depending on the island. For instance, in Unguja, population increase was predicted to occur mostly in the north and south coastal zones where there are existing high levels of tourism, whereas in Pemba it was expected in the urban centres. In this case, there Unguja might need more investment in water infrastructure, even desalination , in coastal sites, whereas in Pemba the demand would be greater in the urban areas. This provides support to the idea ensuring place-based understanding when planning resource security in the future (Käyhkö et al., Berthet et al., 2022). The Kesho approach applied in chapter 4 details key practical steps that can be used for developing an understanding of how drivers and pressures are contextualised across different landscapes. Developing a more accurate understanding of this means that scenario outputs can be more locally relevant and robust.

One of the most significant contributions that the thesis makes is providing a methodological example of how to use local knowledge in land cover modelling processes for developing scenarios towards sustainability. The research process supported participants to frame their resource challenges and reflect on how they connected to land use and land cover. In doing so, communities began to recognise the interactions and were better able to evaluate how different interventions might influence water-energy-food security in the future. They were also able to provide detail with regards to which variables would cause great land cover transitions and locations where land cover transitions were more likely to occur. This meant that community insights could be directly applied to the modelling process, which is a key function of the Kesho approach introduced conceptually in chapter 1 and more practically in chapter 4. This enhances the robustness of the final scenarios outputs and means interventions could be appropriately applied, i.e., reforestation of areas predicted to experience a loss in permanent waterbody cover. This more inclusive approach to land cover modelling has been applied in the Southern Agricultural Growth Corridor Kilombero, southwest Tanzania (Thorn et al., 2022), in the Serengeti landscape for pastoral transitions (Kariuki et al., 2022) and to evaluate social-ecological transitions in Kenya and Ethiopia (Capitani et al., 2019).

What is different in the case of this research as opposed to other Kesho applications is the level of in depth community-based research that informed the scenarios process. Whilst stakeholder engagement across diverse sectors has been central to all Kesho processes (ie. Capitani et al., 2016; Capitani et al., 2019, Kariuki et al., 2022), there had not yet been an approach which has centred communities and their needs in the Kesho scenario process through community level engagement. Within this thesis, an approach was taken to create a common vision for future planning - water-energy-food security. Steps were taken to create long-lasting relationships with communities across diverse land cover types to build an understanding of contextual differences, as well as similarities. Place-based understandings were then be used to identify where national policies for land cover change might be appropriate, and where flexibility would be needed to ensure appropriateness. As a result, the methodology developed could be used to enable more effective incorporation of communities insights, experiences and values into scenario planning.

This said, there are limitations that were recognised through this process that could be addressed in the continued evolution of the Kesho approach. One thing that was observed was that the scenarios narratives were bounded by the experience of participants in terms of what they knew to be possible. Without having insights about really different ways of approaching futures it is really challenging for local stakeholders to push for more ambitious change. When the participants evaluated the potential effectiveness of the scenarios to strengthen water-energy-food security, none of the potential pathways seemed to fully address existing and emergent challenges. This indicates that transformative change may be needed to make the shift from insecure resources to sometime more reliable and stable (Patterson et al., 2017; Rakhmatullaev et al., 2018;). Scenarios for transformation may require a research methodology which supports stakeholders to identify how the current political, social, cultural and economic systems currently shape social-ecological relationships around resources (Horan, 2019; Krueger et al, 2022). Alongside this, there is a need to create space for expanding possibilities, experimenting with innovative ideas and recognising how to leverage changes in systems to enable different pathways to resource security (Hoolahan et al., 2019; Chapin et al., 2022).

Participants in this study collectively advocated for mechanisms to advance political capabilities in decision-making, value shifts to ensure that community needs were central to decision-making and better integration between sectors. What could be really useful in future applications to

Kesho is to dedicate more focus to the conditions needed for change and how these could be implemented. In this case the focus might have been how can decision-making bodies better recognise local community agency in their processes, alongside exploration of kinds of evaluation could ensure that decisions are made according to the needs and values of those affect by those decisions and identification of the kind of institutional support is needed to ensure that integration between sectors happens.

Whilst scenario planning has become influential for decision making processes when attempting to mediate multiple challenges (Hoolahan et al., 2018) – they are still bounded by what stakeholders expect could happen. As aforementioned, this research was conducted in 2019, just before the covid pandemic, and it's interesting to reflect on the drivers of change which were identified as having major influence of land use and land cover considering what was observed in the years post 2020. Tourism is a major contributor to Zanzibar's GDP, and the sudden and long lasting closing of borders had a major impact on the country's economy and local livelihoods. Whilst there is little research on the profound impact that the pandemic had on communities in Zanzibar, I was based in Unguja island from October 2020 through until March 2023 and observed several impacts.

On the outset of the pandemic, there was an immediate loss of income, and the vast majority of people reverted to subsistence based livelihoods of fishing and farming. This showed that the transition to a bought food economy had left local people extremely vulnerable to perturbations in income. While communities in Zanzibar are skilled in subsistence farming, the challenges, related to climate change and soil fertility limited its potential to meet food needs. As a small island, Zanzibar relies heavily on food imports, which were disrupted during the pandemic and led to price spikes, compounding the effects of loss of income.

The Zanzibar government then established a new chartered flight from Russia, one of the few countries which was beginning to allow travel. At this point tourism increased, but there was an observation that they had different interest to previous visitors and did not typically engage in excursions or buy local crafts – meaning informal income opportunities which many Zanzibari's rely on were still not sufficient. At the same time there were tourists who enjoyed the freedom Zanzibar had to offer with the lack of covid restrictions in place and looked for opportunities to buy land. What followed was that a number of local people who had depleted all other options sold their family land at extremely low prices. In the years between 2021 and 2023 tourist visits increased and there continued to be a high level of interest in buying land. House and hotel construction increased dramatically. In parallel to this, there were challenges obtaining construction imports to Zanzibar, meaning a reduction in cement and other construction materials

- which put pressure on local resources and local people being able to afford materials. As a result the pandemic had both immediate and long lasting effect on land cover, access to resources and peoples capabilities to adapt to future changes due to loss of land assets.

This sudden and unexpected shock was not foreseen in the scenario development process, and its likely to have completely altered the nature of how both communities and key stakeholders would view and plan for change. It shows the importance of planning for uncertainty and pressures yet to be uncovered. As a result, for scenarios to be effective there might be a greater emphasis on how to increase capabilities of people, households, communities and society when faced with unforeseen change. The Kesho process might open discussions around capacities for coping with both known and unknown change by asking critical questions such as:

- How can agility be strengthened across all levels of society?
- How can cross-sector relationships be facilitated to ensure a more integrated response to change?
- How can the capabilities of local communities be increased so they can better respond to change?

This would mean that the core function of translating local perceptions into scenario planning is retained, but that the social and political aspects of harnessing change become much more central to future visioning.

Reflections

There are also some important reflections to consider when looking back at the process as a whole. In chapter 3, when communities were thinking about solutions to resource challenges, suggestions were made with regards to sociocultural practices. For example, educating younger generations about places of historical, spiritual, and cultural importance, and supporting collaboration, unity and respect between community and government sectors. Some of these themes also came through in the scenario narratives detailed in chapter 4. Upon reflection, I don’t think I fully acknowledged the importance of these factors initially as they did not obviously align with my research framing, which I imagined to be an explicit focus on resources. However, over time (and possibly due to the persistence of communities) I began to recognise that there are deeper layers to how communities experience and value their environment – which extends beyond resource extraction. This made me question my own perceptions. Working with communities that experience poverty, I assumed that resource security was the overriding vital issue. I now realise that this is a quite a restrictive view, which underestimates the value of holistic aspects of social-ecological relationships, including spirituality and well-being. Understanding more as a result of this research process I would take advice from Abu Moghli & Kadiwal (2021) and challenge my way of seeing, knowing and structuring the world in the conceptualisation process. I would also give more attention to my positionality and its influence on the way I frame my research objectives.

Another reflection I have is with regards to how I viewed the significance of findings. In chapter 3, when looking at solutions for challenges associated with water-energy-food security into the future, one participant said she thought there needed to be better family planning advice. The participant had raised it because it because the increase in population meant an increase in resource demand and land use competition. As with the above, I did not initially recognise the importance of that statement, in part because it was only raised once, but also possibly because I was not sure how to discuss the concept in the context I was working in, as ideas around contraception can be contentious (Norris et al., 2011). When I reflect on this, I realise that it may have only been raised once because of my mixed gender sampling approach. I also realise that when conducting research there needs to be level of sensitivity to social issues which can emerge in the process of qualitative fieldwork. In the future, a more flexible approach could be used to clarify unforeseen or contentious concepts that arise. For instance, in this case, I could have organised a focus group with women in collaboration with a trusted local women's NGO.

The final reflection is with regards to the sampling. The data collection occurred in a time when John Pombe Joseph Magufuli was president of Tanzania. It is worth noting that the majority of Zanzibar, especially in Pemba, support the opposition party. Village leaders, however, are all representatives of the ruling party. To undertake research in Zanzibar there is a requirement to form a collaboration with a local government office to support the research permit process. In my case I formed a relationship with the Department of Forestry and Renewable and Non-Renewable Resources. As a part of this relationship, the department offered practical support with fieldwork and forming relationships with village leaders and the village leaders then acted as gatekeepers for inviting community members to focus groups and workshops. During data collection I was surprised at how little people referred to political challenges they faced, as in personal conversations dissatisfaction with politics was frequently raised. On reflection, I think that either the questions in the workshop did not support political considerations enough, or more likely, the presence of government department officials and village leaders limited the expression of more negative comments. Whilst I am not sure I could have avoided this effect; it is something that needs to be considered as a limitation of the research.

Future research agenda

This body of work provides a key contribution towards centralising social-ecological understanding of the water-energy-food nexus into scenario development. Through the process of this work it also uncovers pertinent research questions to inform future research agendas:

- How can governance arrangements better recognise the agency of local communities and create clear mechanisms to increase political capability?
- What kinds of capabilities are most effective for enhancing communities ability to be agile to unforeseen change – and how can they be strengthened?
- What effect does an increase in local migration have on societal structure and in turn land use and land cover?
- Does institutional deliberation and collaboration create opportunities for more synergistic approaches to resource management?
- How can nature-based resources be regeneratively managed to ensure that local needs are met whilst preventing depletion?
- How can small islands increase their transformability when faced with unpredictable change?

Conclusion

Small developing islands face myriad pressures to resource security, resulting from increasing demand, exposure to climate threats, small size, and fragile ecosystems. Both temporal and spatial characteristics of landscapes in small islands mediate if and how shocks and stresses associated with such pressures are experienced. Considering the rapid nature of land use and land cover change in small islands, these characteristics need to be understood, so that opportunities are harnessed, and emerging challenges are effectively remediated. For this to be meaningful, there is a need to explore resources using a nexus approach, so that synergies and trade-offs of future planning decisions can be explored. This requires an in depth understanding of social-ecological relationships, but often nexus research focuses on systems without fully acknowledging the people who operate and exist within them. This research used a social-ecological framing to understand the water-energy-food nexus and connected these insights to scenarios development using the Kesho approach. In doing so, the study found that there were key drivers of change which impact the water-energy-food nexus at a national level, but that these manifest in different ways for Pemba and Unguja. The study also showed that scenarios narratives for the two islands had many alignments, especially strategically; but that when applied to future scenarios land cover modelling had different influences of land use and land cover for Pemba and Unguja. Consequently, findings highlight the need for place-based research and an awareness that policy decisions around land use and land cover can be contextualised in different ways according to the economic, social, cultural, and environmental characteristics of a place. Findings also show that people living in small developing islands experience resource insecurity at present, and that these are likely to exacerbate rapidly as pressures continue. Stakeholders in the scenarios process advocated for meaningful inclusion of communities in decision-making and better integration of knowledge across all associated sectors to address interrelated challenges. Future research needs to investigate how this can be facilitated effectively so that rapid solutions to ongoing and emergent resource insecurity can be actioned.

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APPENDIX

APPENDIX 1.1: FOCUS GROUP TOPIC GUIDE FOR THE SCOPING INTERVIEWS

1. **Topic guide**

Section 1: Background information

Households

- Within the village what are the different types of household composition (ie families, friends' colleagues)??
- Is there any rented or shared accommodation facilities, such as dorms or staff houses?
- Have these always existed or are they a new development?
- What are the different types of land tenure in the village (ie. owned, rented)??
- Has the land been passed down between generations or do people tend to buy their own plots nowadays?
- If renting - who are they renting from?
- How do people set up their household plots? Do they have shambas, trees or livestock within their plots or are these in separate areas?

Livelihoods

- What tends to be the domestic role of the adult males and females in the family?
- How are these roles changing across different generations?
- Why do you think that they are changing?
- What are the duties undertaken by children in the village?
- Are the duties of girls and boys different?
- At what age do children begin helping to undertake these activities?
- Do men and women both engage in employment or income generating activities?
- Which type of activities to men tend to do?
- Which type of activities do women tend to do?
- Has this always been the case or have there been some changes over the last 20 years?

- What do you think has caused those changes?
- Are the younger generations continuing to carry out traditional activities or are they finding different types of work?
- Why do you think this is?
- In terms of [livelihood activities stated above] have there been any emerging challenges in the last 20 years?
- How are people responding to such challenges?

Population

- Approximately how many people are living in the village at present?
- Over the last twenty years has the population increased, decreased or stayed the same?
- What has driven these changes?
- Do you have many people moving into the village from other areas?
- Are people moving from different places within the island or externally?
- When did this start to happen?
- Why do you think this started to happen?
- Has this been a steady increase or are their times where it has happened more or less?
- Do you have many people from the village moving out of the village to elsewhere?
- Why do you think this is?
- When did this start to happen?
- Has internal or external migration had an impact on the social structures within the community?
- Do you think the movement of people as had any economic implications?
- Has the changing population or socio-demographic situation impacted on the security of energy, water or food in any way?

Section 2: water, energy and food nexus questions

Water

- How do people in the village obtain water? (ie by public well or tap, or piped)

- Who provides public water?
- Do people to pay for water?
- Where is the water piped from?
- Typically, how much water might a household use in a day (number of Jerry cans)?
- Is there a consistent/steady supply of water?
- What do people do if or when there is not a consistent supply of water?
- Whose role within the family is it to collect water?
- How long does it take generally to do this?
- What are people using the water for (cooking, drinking, washing, bathing, building, agriculture)?
- Do people use a different water supply for different water related activities?
- Are there any water use conflicts between these activities (ie human and livestock use)?
- Does anyone in the village receive piped water?
- How often does it arrive in the home?
- How do people know when the water is coming?
- If or when the piped water doesn't arrive at the home what are people doing to get enough water?
- What do you think about the quality of the water?
- Do you treat the water before drinking?
- How do you treat the water?
- Do many people suffer with water borne illnesses?
- Do you think there are any noticeable links between changing land use and water availability here ie deforestation?

Energy – firewood

- How much charcoal/firewood might one household use per day (kg?)?
- Do people within this community tend to buy the firewood/charcoal or collect/make themselves?
- Whose responsibility is it to collect/make the firewood/charcoal?

- Where to people tend to get the firewood from?
- How far is the forest from the village (km)?
- What is the current condition of the forest?
- Are there any restrictions of forest use?
- What is the quality of firewood like?

Energy – electricity

- Do many people have electricity in their homes?
- How is this obtained – through the grid or solar power?
- How recently has electricity been used within the villages?
- How much does it cost (Tsh/month)?
- Does this cost provide a barrier to some people? If yes, who?
- Is there a secure supply of electricity?
- What do people tend to use electricity for? (e.g. cooking, heating, lighting, etc.)
- How do people without electricity manage (ie do they use other people's electricity supply)?
- Which types of energy are used for cooking or boiling water (ie firewood, charcoal, kettle or small hob)?

Food

- What are the typical types of meal that people cook in the village?
- Do people tend to buy food or produce food themselves? (span question over vegetables, meat, fish, rice, grains)
- Has this changed over time? If so why?
- Has the price of food increased, decreased or stayed the same over the last 20 years?
- Why do you think this is?
- Is there a steady supply of food across the seasons (span question over grains, fish, meat, vegetable and fruit)?
- How many months of the year would you say there is a steady supply of nutritious food?

- If/when food becomes scarce how do people cope?
- How have people's diets changed in the last 20 years?
- Why do you think this is changing?

Section 3: drivers of change questions

- Has there been a change in the sea level or temperature of the sea in the last 20 years?
- Has this had any implications for coastal livelihood activities?
- Do you experience flooding in the village?
- Is this a new occurrence?
- Can you describe a time when this happened?
- How did it impact on the community?
- How did the community respond?
- How did the government respond?
- Have there been any changes to patterns of rainfall in the last 20 years?
- What has the impact of this been on communities?
- How have people responded to such change?
- Have there been any infrastructure developments in and around the village in the last 20 years?
- What impact has this had at the village level?
- Has this effected food, water or energy security in any way?

Section 4: final questions

- Overall, how do you think things have changed in the village since you were young?
- What do you think are the biggest challenges facing your village for the future?
- How to you think land use or land cover might change in the next 10 years?
- What impact do you think this would have on the next generation of children?
- What would a desirable future be for the next generation of children here?
- What would the community be interested in better understanding?

- Are there challenges related to food, water or energy that we have not addressed within these questions?
- Is there anything you would like this research project to address or explore?
- Do you have any questions or comments for us?

Appendix 2: Supplementary information for the community based workshops chapter

1. Age range of participants

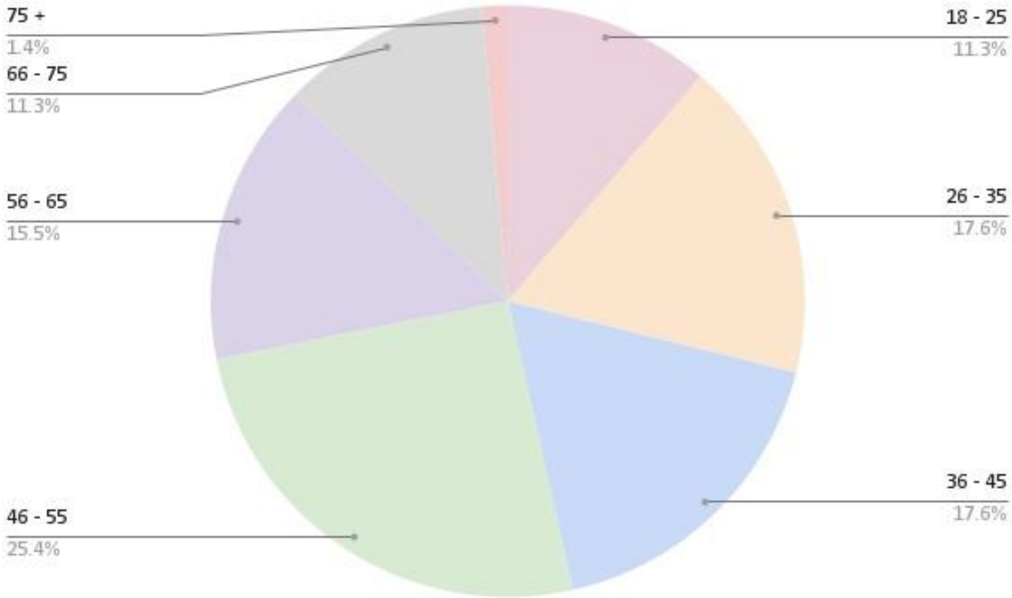

Figure 1. Average age ranges of participants in Unguja and Pemba workshops

2. Distribution of identified livelihood activities in Unguja and Pemba

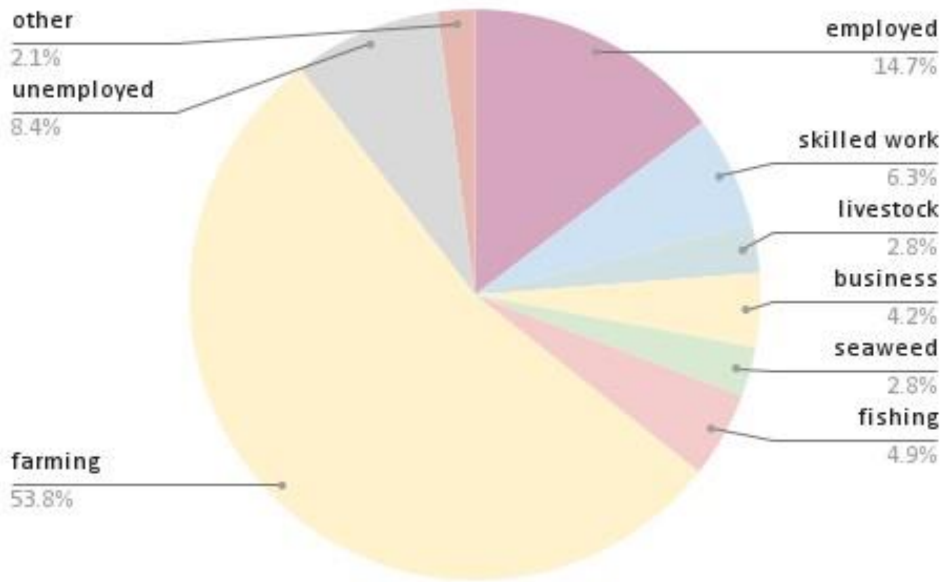

Figure 2. Core livelihood activities participants identified with.

3. Order of the day

Time	Activity
9.00 am – 9.30 am	• Registration and introduction to the project
9.30 am – 10 am	*Breakfast*
10 am – 11 am	• Participatory mapping of land use and land cover in the village today and discussion about how water, energy and food needs are met • Evaluation of water, energy, food exercise for present day
11.00 am – 11.30 am	*Break*
11.30 am – 1.00 pm	• Participatory mapping of land use and land cover in the village 10 years ago and discussion about how water, energy and food needs were met • Evaluation of water, energy, food exercise for the past
1.00 pm – 2.00 pm	*Lunch*
2.00 pm – 3.30 pm	• Explore the differences in land use and land cover across the two maps and identify causes of those changes • Reflect on the list of causes/drivers and select those which might be most pertinent for the next 20 years • Envisioning land use and land cover in the village 10 years from today in a Business as Usual (BAU) scenario and • Evaluation of water, energy, food exercise in a BAU scenario
3.30 pm – 4.00 pm	*Break*
4.00 pm – 5.30 pm	• Identify any emergent challenges for water, energy and food security in a BAU scenario • Suggest potential ways to address such challenges

4. Identified drivers in each workshop (top three most prevalent)

Table 1. The full list of drivers and their respective votes for each site. A total of 24 drivers were identified between sites.

***Shehia* areas in Pemba**	**Drivers of change identified**	**1**	**2**	**3**
Macho mane and Mkoroshoni	population increase	12	1	0
Macho mane and Mkoroshoni	climate change	2	6	3
Macho mane and Mkoroshoni	development	0	4	6
Macho mane and Mkoroshoni	loss of soil fertility	0	2	3
Macho mane and Mkoroshoni	advancements in technical farming	0	2	1
Mji Mpya	population increase	1	1	4
Mji Mpya	climate change	0	6	1
Mji Mpya	air pollution	4	0	2
Mji Mpya	development	1	3	2
Mji Mpya	over extraction of water	2	0	0
Mji Mpya	loss of soil fertility and high chemical input	0	2	4
Mji Mpya	deforestation	5	0	1
Mfikiwa	population increase	6	1	3
Mfikiwa	socio-economic development	2	1	1
Mfikiwa	climate change	2	5	1
Mfikiwa	over farming	1	4	2
Mfikiwa	deforestation	2	2	6
Wambaa and Chumbageni	development	5	2	1
Wambaa and Chumbageni	population increase	7	3	0
Wambaa and Chumbageni	increase in forest management	0	3	0
Wambaa and Chumbageni	increase in tourism	0	1	2
Wambaa and Chumbageni	climate change (weather)	1	1	1
Wambaa and Chumbageni	climate change (sea-level rise)	0	3	2
Wambaa and Chumbageni	deforestation	1	1	7
Pujini and Dodo	population increase	9	0	1
Pujini and Dodo	development	2	1	1
Pujini and Dodo	climate change	1	1	3
Pujini and Dodo	deforestation	0	2	3
Pujini and Dodo	unemployment	1	2	4
Pujini and Dodo	pest outbreaks	0	7	1
Pete	increase in ecotourism	4	0	0
Pete	deforestation	1	1	2
Pete	poverty	2	4	2
Pete	decrease in soil fertility	2	1	3
Pete	climate change	3	2	2
Pete	overfishing	2	2	1
Pete	decrease in nutritious food	0	0	3
Pete	population increase	0	3	2
Pete	development	1	3	0
Pongwe	sea level rise and sedimentation	0	0	0
Pongwe	unpredictable rainfall (climate change)	0	0	7
Pongwe	loss of soil fertility	0	0	10

Pongwe	change in cultivation (crops to forest)	5	0	1
Pongwe	population increase	5	5	0
Pongwe	socio-economic development	5	4	0
Pongwe	increase in tourism	1	6	0
Pongwe	technological advancement	1	2	0
Pongwe	unsustainable fishing	0	0	0
Pongwe	road development	0	0	0
Kizimbani	increase in education	2	4	0
Kizimbani	increase in ecotourism	1	1	0
Kizimbani	socio-economic development	0	4	3
Kizimbani	lack of water management	0	0	3
Kizimbani	poor settlement planning	1	0	1
Kizimbani	deforestation (poor regeneration)	3	1	1
Kizimbani	loss of natural soil fertility	0	1	2
Kizimbani	population increase	6	1	3
Kinyasini	increase in farming technology	1	2	1
Kinyasini	increase in road infrastructure	1	3	0
Kinyasini	increase in education	1	4	1
Kinyasini	population increase	3	0	3
Kinyasini	socio-economic development	0	1	1
Kinyasini	increase in water management	0	1	1
Kinyasini	lack of settlement planning	2	0	0
Kinyasini	land shortages/conflict	1	3	1
Kinyasini	deforestation	2	0	3
Kinyasini	climate change	3	0	3
Jambiani	increase of tourism	5	3	3
Jambiani	sea level rise	2	3	2
Jambiani	population increase	0	5	4
Jambiani	climate change	2	0	1
Jambiani	shifting plot (sea level rise and tourism)	2	1	1
Jambiani	socio-economic development	2	1	2

5. Distribution of the recommended solutions

		Sustainable settlement planning	Protection and regeneration of ecosystems	Improving adaptive capacity	Family planning	Maintaining cultural values
Pemba	Macho mane and Mkoroshoni	5	4	5	1	0
	Mfikiwa	5	3	3	1	0
	Mji Mpya	6	7	5	0	0
	Pujini and Dodo	4	4	3	0	1
	Wambaa and Chumbageni	7	5	6	0	0
Unguja	Jambiani	3	0	0	0	3
	Kinyasini	2	4	4	1	0
	Kizimbani	3	0	3	0	2
	Pete	4	3	2	0	3
	Pongwe	2	3	3	0	2
	Total	**41**	**31**	**34**	**3**	**11**

Low High

Figure 3. The distribution of recommended solutions by site, the top five sites are in Pemba Island and the bottom five site are in Unguja.

Appendix 3: Supplementary material explaining aspects of the modelling process for the Kesho scenarios process

1. Guidance for scenario narrative formation

To stimulate conversations amongst participants while defining the narratives underpinning the scenario options for these questions were suggested. However, these were a guide only.

Table 1. Guiding questions for scenario narrative formation in Pemba and Unguja multistakeholder workshops.

Pathway	Guiding questions
Improving the adaptive capacity of communities	● What are the biggest challenges facing local livelihoods today? ● How are people currently responding to those challenges? ● Are people's current response strategies adequate for dealing with change or not? ● What kind of training and education is needed to help people overcome these emerging challenges? ● Are there any specific areas in Zanzibar that need to prioritise? If so, explain why. ● Which sectors or organisations should be involved in providing education and training? ● Are there any barriers to people accessing education and training? ● How might these barriers be overcome?
Protection and regeneration of ecosystems – with consideration to areas of cultural and spiritual importance	● Which ecosystems are important to protect and why? ● Which types of ecosystems are important to regenerate and why? ● Why were these ecosystems degraded or removed before? ● Do communities rely on these types of ecosystems for their livelihoods? ● Are there external pressures which result in ecosystem degradation or removal? ● What kinds of natural places are of spiritual and cultural importance? ● Are there any areas that need to be highlighted as being of high priority for protection and regeneration? ● How should ecosystems and places of spiritual and cultural importance be protected and regenerated? ● Are there any barriers to successfully protecting ecosystems and places of spiritual and cultural importance?

	● Can these barriers be overcome? If so how? ● Which sectors or groups should be involved in decision making about protecting and regenerating ecosystems and places of spiritual and cultural importance?
Sustainable settlement planning	● How do you think Zanzibar might develop between now and 2030? ● What will be the main economic focus of Zanzibar in the coming years? ● Which areas are most likely to change as a result of socio-economic development? ● How can communities in these areas be affected? What will be the positive and negative impacts? ● What role will settlement planning play in supporting sustainable land use? ● What specific interventions could be made to support more sustainable settlements? ● What specific interventions are needed to ensure that settlements are planned appropriately? ● As the country develops, are their opportunities for using green/renewable energy sources? ● Which areas are likely to become more urbanised? ● Will there be any resulting losses to environments as a result of urbanisation and if so how could such losses be minimised?

2. Land cover classes *and data sources*

The terms used on the right hand side were used in the multi-stakeholder workshops to describe land use and land cover change. These do not directly coincide with the land classes in the *Corpencious* maps used in the modelling process. To align the land cover classes, the location of land cover types was compared with a land cover map developed by the Zanzibar's Department of Forestry, Renewable and Non-renewable Resources from 2012. Discussions were also held with other ecological researchers in Zanzibar for advice about how the terms used in the workshops might correspond to the land cover data. One of the most difficult categories to identify within the Copernicu**s** land cover maps was mangroves. The most up to date world land cover map by ESA worldcover includes a mangrove layer for 2020. As there is only a layer for 2020 and not another time step it is not possible to use this more detailed map in the Land Change Modeler analysis. However, by comparing the 2019 map and 2020 map we can see that mangrove forests appear to be encompassed within the 'unknown forest closed' and 'unknown forest open' land categories in specific locations. This also corresponds well with the transitions identified in the land change analysis outputs which show that unknown forest (open and closed) transitioned to wetland vegetation, assuming that deforestation of mangroves resulted in increased wetland vegetation.

Table 2. Land cover class descriptions used in initial modelling process (note these were later simplified further).

Land class	**Description**	**Corresponding land cover classes from workshops**
Shrubland	These are woody perennial plants with persistent and woody stems and without any defined main stem being less than 5 m tall. The shrub foliage can be either evergreen or deciduous.	Native bushland (degraded coral rag forest, but with regeneration/restoration potential)
Herbaceous vegetation	Plants without persistent stem or shoots above ground and lacking definite firm structure. Tree and shrub cover is less than 10 %.	Thin woody vegetation
Cropland	Lands covered with temporary crops followed by harvest and a bare soil period (e.g, single and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.	Mixed farming and commercial farming
Built up	Buildings and other manmade structures.	Built up
Bare or sparse vegetation	Lands with exposed soil, sand, or rocks and never has more than 10 % vegetated cover during any time of the year.	Bare land
Permanent waterbodies	Lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies.	-
Herbaceous wetland	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish, or fresh water.	-
Evergreen broadleaved forest (closed)	Tree canopy >70 %, almost all broadleaf trees remain green year round. Canopy is never without green foliage.	Coral rag forest
Deciduous broadleaved forest (closed)	Tree canopy >70 %, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.	Plantation forest
Unknown forest (closed)	Closed forest, not matching any of the other definitions	Coral rag and other natural forest, in close proximity to the sea this includes mangrove
Evergreen broadleaved forest (open)	Top layer- trees 15-70 % and second layer mixed of shrubs and grassland, almost all broadleaf trees remain green year round. Canopy is never without green foliage.	Coral rag forest
Deciduous broadleaved forest (open)	Top layer- trees 15-70 % and second layer mixed of shrubs and grassland, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods	Plantation forest
Unknown forest (open)	Open forest, not matching any of the other definitions	Coral rag and other natural forest, in close proximity to the sea this includes mangrove
Sea	Oceans, seas. Can be either fresh or salt-water bodies.	-

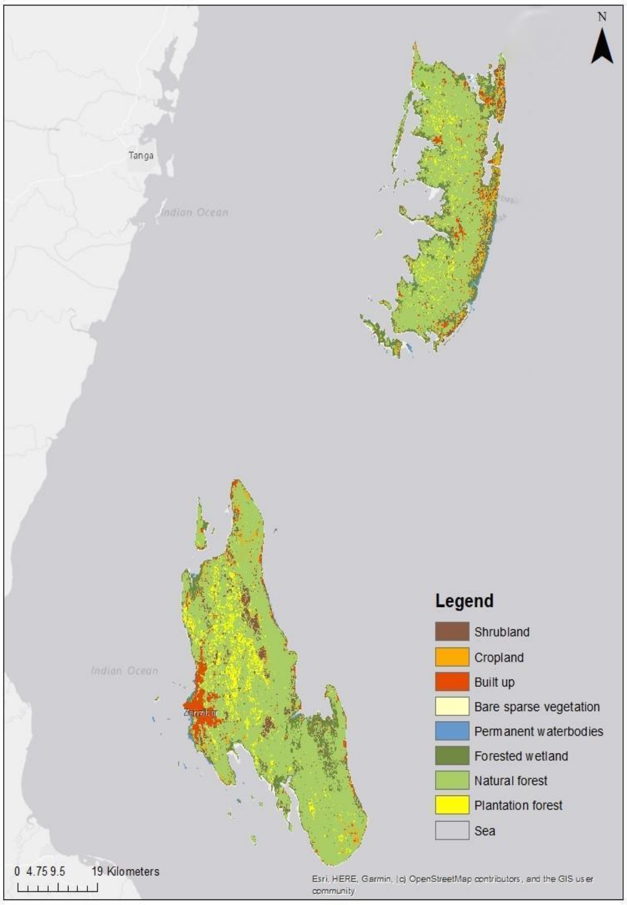

Figure 1. Map of Unguja and Pemba islands and land use and land cover for the year 2019 (when fieldwork was conducted). Land cover calculated using *Copernicus* Global Land Cover data (Buchman et al, 2020), which was modified to encompass scaled knowledge of the local area.

Table 3. Data sources for land cover variable layers

Layer	Resolution	File type	Reference	Website
Land cover 2015	100 m	Tiff	*Buchhorn, M.; Smets, B.; Bertels, L.; Lesiv, M.; Tsendbazar, N.-E.; Masiliunas, D.; Linlin, L.; Herold, M.; Fritz, S. (2020). Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch <YEAR>: Globe (Version V3.0.1) [Data set]. Zenodo. DOI: https://doi.org/10.5281/zenodo.3939038*	*https://lcviewer.vito.be/about*
Land cover 2019	100 m	Tiff	*Buchhorn, M.; Smets, B.; Bertels, L.; Lesiv, M.; Tsendbazar, N.-E.; Masiliunas, D.; Linlin, L.; Herold, M.; Fritz, S. (2020). Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch <YEAR>: Globe (Version V3.0.1) [Data set]. Zenodo. DOI: https://doi.org/10.5281/zenodo.3939050*	*https://lcviewer.vito.be/about*
Elevation	10km	Tiff		*https://asterweb.jpl.nasa.gov/GDEM.asp*
Roads	-	Shp/vector	*Center for International Earth Science Information Network - CIESIN - Columbia University, and Information Technology Outreach Services - ITOS - University of Georgia. 2013. Global Roads Open Access Data Set, Version 1 (gROADSv1). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4VD6WCT. Accessed DAY MONTH YEAR.*	*https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1/data-download#close*
Soil composition	-	Polygon	Panagos, P, Van Liedekerke, M, Borrelli, P, Köninger, J, Ballabio, C, Orgiazzi, A, Lugato, E, Liakos, L, Hervas, J, Jones, A. Montanarella, L. 2022. European Soil Data Centre 2.0: Soil data and knowledge in support of the EU policies. European Journal of Soil Science, 73(6), e13315. DOI: 10.1111/ejss.1331	https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa

3. Sub model compositions for explaining land cover change between 2015 and 2019

Sub models were created to help explain each of the broad land cover transitions identified.

Table 4. Sub model details for transition potential maps explaining land cover change between 2015 and 2017 in Unguja.

Sub model	Transitions	Minimum number of cells	Spatial variables in minimum model sub model structure	Accuracy percentage	Skill score
Sea level	Herbaceous vegetation to herbaceous wetland	428	Slope, soil composition	68.85	0.3570
Water body reduction (mangrove)	Permanent waterbody to herbaceous wetland	251	Slope, distance from roads, distance from protected areas, DEM, distance from wetlands, likelihood of change	71.31	0.462
Deforestation (mature forest)	Unknown closed forest to herbaceous wetland, unknown open forest to herbaceous wetland	870	Slope, likelihood of change	74.51	0.6602
Deforestation (Shrubland)	Shrubland to herbaceous wetland	611	Slope, distance from built up, distance from sea, distance from protected areas, soil composition, likelihood of change	78.07%	0.5613

Table 5. Sub model details for transition potential maps explaining land cover change between 2015 and 2017 in Pemba.

Sub model	Transitions	Minimum number of cells	Spatial variables in minimum model sub model structure	Accuracy percentage	Skill score
Sea level	Herbaceous vegetation to herbaceous wetland	511	DEM, distance from roads, distance from closed forest, distance from sea, soil composition	73.22	0.4645
Water body reduction (mangrove)	Permanent waterbody to herbaceous wetland	463	DEM, distance from closed forest, soil composition	61.04	0.2208
Deforestation (mature forest)	Unknown closed forest to herbaceous wetland, unknown open forest to herbaceous wetland	904	Distance from wetlands, distance from settlements, distance from sea, soil composition and likelihood of change	60.50	0.4734

4. Sample size information for MLP analysis in the Land Change Modeller Process for the BAU Scenario

A sample size of the minimum number of pixels to undergo transition between categories was used to set the sample size of each sub model as exceeding this limit can lead to overfitting the model (Clark labs, 2017). Pixels within the sample are assigned to two groups, half calibrate the model and half validate its performance giving a percentage accuracy rating. A skill statistic is also produced, this varies from -1 to +1, a skill of 1 indicates a perfect prediction whereas a minus score suggests the model is performing worse than change (Clark labs, 2017). The model output performs backwards constant forcing which tests the contribution of each explanatory variable, to make the model more parsimonious the minimum number of variables was selected for each sub model (Crawley, 2005).

5. Calculations for land demand for the business as usual scenarios

To include expansion of built-up areas in the alternative scenario maps, the difference area between 2015 and 2019 for the built-up category was calculated using the known land cover data sets from *Corpencious*. The difference was calculated as a factor for the annual rate of change and the following calculation was then conducted to determine the total area demand for built up land in 2030 :

$$Annual\ rate\ of\ change = \frac{Difference\ in\ area\ between\ 2015\ and\ 2019}{Average\ area\ respective\ of\ 2015\ and\ 2019}$$

Table 6. Area of built up land cover class

Year	Built up area Pemba (ha)	Built up area Unguja (ha)
2015 (actual)	0.830265	2.243410
2019 (actual)	0.833215	2.253717
2030 (bau model)	0.833215	2.253717

Calculation for annual rate of area change for the built up land class in Pemba (ha):

$$Annual\ rate\ of\ change = \frac{0.833 - 0.830}{(0.830 + 0.833)/2}$$

$$Annual\ rate\ of\ change = 0.004$$

Calculation for annual rate of area change for the built up land class in Unguja (ha):

$$Annual\ rate\ of\ change = \frac{2.254 - 2.243}{(2.243 + 2.254)/2}$$

$$Annual\ rate\ of\ change = 0.005$$

Demand for built up land area calculation:

$$Future\ surface\ = present\ surface\ \times\ [1 + Annual\ rate\ of\ change] \wedge number\ of\ years$$

Calculation for built up land class demand for 2030 in Pemba (ha):

$$Future\ surface = \ 0.833\ \times (1 + 0.004)\hat{}11$$

$$Future\ surface = \ 0.871$$

Calculation for built up land class demand for 2030 in Unguja (ha):

$$Future\ surface = \ 2.253717 \times (1 + 0.005)\hat{}11$$

$$Future\ surface = \ 2.381$$

Increase in land demand for built up class from current bau model for Pemba (ha):

$$Additional\ land\ demand = \ 0.871 - 0.833$$

$Additional\ land\ demand =$ 0.037

Increase in land demand for built up class from current bau model for Unguja (ha):

$Additional\ land\ demand =$ 2.381 – 2.254

$$Additional\ land\ demand = \ 0.127$$

Note that for the spatial decision modeller, the demand allocation needs to be in pixels. In Pemba 1 ha was equal to 2712.39 cells, the additional land demand 100 cells (as an integer). In Unguja 1 ha was equal to 2716.85 cells so the additional land demand was equal to 345 cells (as an integer).

Using the reclass function in TerrSet, Boolean constraint maps were created to ensure that potential land transitions to the built up class would not occur in existing built up areas, sea, permanent water bodies, wetlands or protected areas. Decision variables including distance from built-up, distance from sea, distance from settlements, distance from roads and slope were then converted into factors with a likelihood scale of 0-1 using the fuzzy module. A suitability image for land cover transition was created using multi-criteria analysis. The allocation of land according to the specified demand was then calculated using the multiple land allocation tool (MOLA). Using MOLA it is possible to specify contiguity and compactness, however as all sampled villages indicated expected settlement expansion this criterion was not selected for in this case. The modelled business as usual (BAU) land cover maps and the spatial allocation maps for additional build up areas were then brought into ArcMap 10.8.1. Using the conditional evaluation tool, the pixels for additional built up areas from the spatial allocation map were applied to the modelled BAU land cover maps. This increased the built up land allocation from 0.833 ha to 0.871 ha in Pemba and 2.254 ha to 2.831 ha in Unguja for the 2030 BAU scenario.

Decisions about the shape of the function and its control points were based on observations of where current built up locations are on the 2019 land cover maps for Pemba and Unguja. The main observed difference between the islands was that in Pemba settlements are more frequently found inland and in Unguja these are more concentrated at the coast. The following assumptions were made that expansion of built up areas (in Unguja especially) would be more concentrated on the coast, close to existing settlements, close to existing road infrastructure and on lower sloped areas.

Table 7. Fuzzy operation details for the decision variables influencing the spatial allocation of additional built up land in Pemba.

Variable name	Function shape	Function type	Control points
Distance from built up	Monotonically decreasing	Sigmoidal	c: 0.02; d: 0.03
Distance from sea	Symmetric	Sigmoidal	a: 0; b: 0.0036; c: 0.004; d: 0.063
Distance from roads	Symmetric	Sigmoidal	a: 0; b: 0.001; c: 0.002; d: 0.01
Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.001
Slope	Monotonically decreasing	Sigmoidal	c: 9.15; d: 14.88

Table 8. Fuzzy operation details for the decision variables influencing the spatial allocation of additional built up land in Unguja.

Variable name	Function shape	Function type	Control points
Distance from built up	Monotonically decreasing	Sigmoidal	c: 0.02; d: 0.03
Distance from sea	Symmetric	Sigmoidal	a: 0; b: 0.001; c: 0.003; d: 0.004
Distance from roads	Symmetric	Sigmoidal	a: 0; b: 0.001; c: 0.002; d: 0.01
Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.001
Slope	Monotonically decreasing	Sigmoidal	c: 5.9; d: 11.79

Table 9. Multi-criterion evaluation (MCE) weights Pemba.

Fuzzy outputs	Weights
Distance from sea	0.0333
Slope	0.0734
Distance from settlements	0.0879
Distance from roads	0.2565
Distance from built-up	0.5489
Distance from sea	0.0333

Table 10. Multi-criterion evaluation (MCE) weights Unguja.

Fuzzy outputs	Weights
Distance from roads	0.0380
Distance from sea	0.0333
Distance from settlements	0.1619
Slope	0.2004
Distance from built-up	0.5664
Distance from roads	0.0380

6. Model conditions for creating the land cover scenario maps for the three alternative options, differentiated by island

For constraint maps *Corpencious* land cover layers were used, these were converted into Boolean maps in IDRISI using the function Reclass to give all land cover types where change could occur a value of 1 and land cover types where change could not occur a value of 0.

Some groups discussing land cover transitions specified specific ward (or Shehia) areas where change would be more likely to occur. To convert this information into spatial data used a Tanzania ward layer in ArcMap 10.8.1, I clicked on editing and start editing to select the specific ward area. I then went to the menu at the top and in the dropdown menu for "geoprocessing" I selected "clip". I then had to alter the extent of the clipped layer to coincide with previously used spatial variables. To do this I opened Arc Catalogue and right clicked on the new clipped layer and in the properties pop out box was able to alter the feature extent manually. Once the extent matched that of the other spatial variables, I was able to use Euclidean Distance to calculate distance from ward. These raster layers were saved as ASCII files to be reconverted into raster's in IDRISI.

In addition to the variables specified within the multistakeholder workshops we also added other variables which had been indicated in the initial scoping study (see Newman et al, 2023a) and community level workshops (see Newman et al, 2023b). Where possible specific spatial parameters from wider literature were also used.

Pemba scenario 1 adaptive capacity

Table 11. Modelling conditions for the adaptive capacity scenario in Pemba. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	Take from land classes (likelihood 0-4)	Constraint map components	Variables influencing transition according to stakeholders	Variables influencing transition according to literature
Built up 0.019	Cropland - 3 Shrubland - 3 Herbaceous vegetation -2 Unknown forest (closed) – 4 Unknown forest (open) - 4	Built up, bare sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), sea	Distance from Vitongoni for losses of unknown forest, distance from Mbuzini for losses in shrubland	Distance from sea, distance from roads, distance from existing settlements, slope
Bare sparse vegetation 0.003	Deciduous forest (closed) – 3 Deciduous forest (open) – 3	Shrubland, herbaceous vegetation, cropland, built up, bare sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), unknown forest (open), sea	-	Distance from settlements, distance from roads, distance from evergreen forests, distance from unknown forests, distance from shrubland, slope
Cropland 0.178	Evergreen forest (closed) – 2 Evergreen forest (open) – 2 Unknown forest (closed) -2 Unknown forest (open) -2	Shrubland, herbaceous vegetation, cropland, built up, bare sparse vegetation, permanent waterbodies, herbaceous wetland, deciduous broadleaved forest (closed), deciduous broadleaved forest (open), sea	Distance from Pujini	Distance from existing cropland, distance from permanent waterbodies, distance from settlements, distance from roads, slope
Shrubland 0.023	Evergreen forest (open) – 2 Unknown forest (open) – 2 Cropland - 2	Shrubland, herbaceous vegetation, built up, bare sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), deciduous broadleaved forest (open), sea	Distance from Ngezi forest	Distance from settlements, distance from roads, distance from unknown forests, slope

Table 12. Fuzzy operation details for the decision variables influencing the spatial allocation of four land cover transitions outlined in scenario one (adaption) for Pemba; T1 – to built up, T2- to bare sparse vegetation, T3 – to cropland, T4 – to shrubland.

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from roads	Monotonically decreasing	Sigmoidal	c: 0.02; d: 0.03
T1	Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.001
T1	Slope	Monotonically decreasing	Sigmoidal	c: 5.9; d: 11.79
T1	Distance from sea	Monotonically decreasing	Sigmoidal	c: 0.02; d: 0.03
T1	Distance from built up	Monotonically decreasing	Sigmoidal	c: 0.02; d: 0.03
T1	Distance from Mbuzi district	Monotonically decreasing	Sigmoidal	c: 0.03; d: 0.05
T1	Distance from Vitongoni district	Monotonically decreasing	Sigmoidal	c: 0.03; d: 0.05
T2	Distance from evergreen forest	Monotonically increasing	Sigmoidal	a: 0.01; b: 0.03
T2	Distance from roads	Monotonically decreasing	Sigmoidal	c: 0.001; d: 0.01
T2	Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.01
T2	Distance from shrubland	Monotonically increasing	Sigmoidal	a: 0.00; b: 0.02
T2	Slope	Monotonically decreasing	Sigmoidal	c: 5.9; d 11.79
T2	Distance from unknown forest	Monotonically increasing	Sigmoidal	a: 0.00; b: 0.02
T3	Distance from cropland	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.02
T3	Distance from permanent water	Monotonically decreasing	Sigmoidal	c: 0.01; d: 0.04
T3	Slope	Monotonically decreasing	Sigmoidal	c: 5.9; d: 11.79
T3	Distance from roads	Monotonically decreasing	Sigmoidal	c: 0.001; d: 0.01
T3	Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.01; d: 0.02
T3	Distance from unknown forests	Monotonically increasing	Sigmoidal	a: 0.00; b: 0.02

T3	Distance from Pujini	Monotonically decreasing	Sigmoidal	c: 0.01; d: 0.02
T4	Distance from roads	Monotonically decreasing	Sigmoidal	c: 0.001; d: 0.01
T4	Distance from settlements	Monotonically decreasing	Sigmoidal	c: 0.0001; d: 0.01
T4	Slope	Monotonically decreasing	Sigmoidal	c: 5.9; d: 11.79
T4	Distance from unknown forests	Monotonically increasing	Sigmoidal	a: 0.00; b: 0.02
T4	Distance from Ngezi forest	Monotonically decreasing	Sigmoidal	c: 0.04; d: 0.11

Table 13. Multi-criterion evaluation (MCE) weights Pemba scenario one, transition one.

Fuzzy outputs	**Weights**
Distance from roads	0.1606
Distance from sea	0.1228
Distance from settlements	0.1119
Slope	0.1957
Distance from Mbuzi district	0.2045
Distance from Vitongoni district	0.2045

Table 14. Multi-criterion evaluation (MCE) weights Pemba scenario one, transition two.

Fuzzy outputs	**Weights**
Distance from evergreen forest	0.2262
Distance from roads	0.0958
Distance from settlements	0.0643
Distance from shrubland	0.1159
Slope	0.3582
Distance from unknown forest	0.1396

Table 15. Multi-criterion evaluation (MCE) weights Pemba scenario one, transition three.

Fuzzy outputs	**Weights**
Distance from cropland	0.4307
Distance from permanent waterbodies	0.0484
Distance from roads	0.0795
Distance from settlements	0.0959
Slope	0.0412
Distance from unknown forest	0.0412
Distance from Pujini	0.2631

Table 16. Multi-criterion evaluation (MCE) weights Pemba scenario one, transition four.

Fuzzy outputs	Weights
Distance from roads	0.0813
Distance from settlements	0.0458
Slope	0.1705
Distance from unknown forest	0.1705
Distance from Ngezi forest	0.5320

Using these conditions, the following a map was produced, however this did not represent some the broader transitions represented in the 2030 prediction produced using the Land Change Modeller Analysis which largely demonstrated transitions to herbaceous wetland. To improve the potential accuracy of the model these transitions were applied to the alternative scenario maps.

To improve to accuracy of the model the transition to herbaceous wetland from the Land Change Modeler process was also added to the scenario. The variables influencing the transition were taken from the sub models detailed in SM3, these included from wetland vegetation, permanent waterbodies and unknown forests. Most of the changes occurred in the CMfl soils, in the transition from unknown forest to herbaceous wetland a constraint map was used to limit changes to areas with this soil type. It was not possible to apply the soil constraint map to the permanent water and herbaceous vegetation transitions to wetland and these parcels of land predominantly lied outside of this type of soil composition. Instead of using the total area of change for this transition outlined in the BAU scenario a more conservative estimate was applied using the minimum expected number of cells per transition as a guide.

Unguja scenario 1 adaptive capacity

Table 17. Modelling conditions for the adaptive capacity scenario in Unguja. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	**Take from land classes (likelihood 0-4)**	**Constraint map components**	**Variables influencing transition according to stakeholders**	**Additional variables influencing transition according to literature**
Built up 0.0254	Cropland – 1 Unknown forest (closed) - 3	Shrubland, herbaceous vegetation, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	Distance from existing built up areas, distance from sea	Distance from roads, slope
Evergreen forest (closed) 0.46557	Shrubland - 2	Cropland, built up, herbaceous vegetation, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	-	Distance from built up, distance from roads, slope
Cropland 0.0064	Evergreen forest (closed) – 1 Deciduous forest (closed) - 3	Shrubland, cropland, built up, herbaceous vegetation, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	-	Distance from existing cropland, distance from evergreen forest (close), distance from deciduous forest (closed), distance from built up, distance from roads, slope
Shrubland 0.02173	Unknown forest (closed) – 1 Herbaceous vegetation - 2	Shrubland, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	Distance from community managed forests (layer used – distance from built up)	Distance from existing cropland, distance from unknown forest (closed), distance from herbaceous vegetation, distance from roads, slope

Table 18. Fuzzy operation details for the decision variables influencing the spatial allocation of four land cover transitions outlined in scenario one (adaption) for Unguja; T1 – to built up, T2- to evergreen forest (closed), T3 – to cropland, T4 – to shrubland.

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from roads	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T1	Slope	Sigmoidal	Monotonically decreasing	c: 0.74; d: 3.69
T1	Distance from built up	Sigmoidal	Monotonically decreasing	c: 0.01; d: 0.03
T1	Distance from sea	Sigmoidal	Monotonically decreasing	c: 0.02; d: 0.03
T2	Distance from roads	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T2	Distance from built up	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T2	Slope	Sigmoidal	Monotonically decreasing	c: 0.01; d: 4.42
T3	Distance from cropland	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.02
T3	Distance from deciduous forest (closed)	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.02
T3	Distance from evergreen forest (closed)	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T3	Distance from roads	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T3	Distance from built up	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.02
T3	Slope	Sigmoidal	Monotonically decreasing	c: 0.01; d: 4.42
T4	Distance from built up	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.02
T4	Distance from cropland	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.02
T4	Distance from roads	Sigmoidal	Monotonically decreasing	c: 0.001; d: 0.01
T4	Slope	Sigmoidal	Monotonically decreasing	c: 0.01; d: 4.42

Table 19. Multi-criterion evaluation (MCE) weights Unguja scenario one, transition one.

Fuzzy outputs	Weight
Distance from roads	0.1463
Slope	0.0547
Distance from built up	0.6263
Distance from sea	0.1726

Table 20. Multi-criterion evaluation (MCE) weights Unguja scenario one, transition two.

Fuzzy outputs	Weight
Distance from roads	0.3333
Distance from built up	0.3333
Slope	0.3333

Table 21. Multi-criterion evaluation (MCE) weights Unguja scenario one, transition three.

Fuzzy outputs	Weight
Distance from cropland	0.4898
Distance from deciduous forest	0.1211
Distance from evergreen forest	0.1211
Distance from roads	0.0719
Distance from built up	0.0980
Slope	0.0980

Table 22. Multi-criterion evaluation (MCE) weights Unguja scenario one, transition four.

Fuzzy outputs	Weight
Distance from built up	0.4099
Distance from cropland	0.2981
Distance from roads	0.2323
Slope	0.0596

To improve to accuracy of the model the transition to herbaceous wetland from the Land Change Modeler process was also added to the scenario. The variables influencing the transition were taken from the sub models detailed above, these included from wetland vegetation, permanent waterbodies and unknown forests and shrubland. Instead of using the total area of change for this transition outlined in the BAU scenario a more conservative estimate was applied using the minimum expected number of cells per transition as a guide.

Pemba scenario 2 ecosystem management

Table 23. Modelling conditions for the ecosystem management scenario for Pemba. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	**Take from land classes (likelihood 0-4)**	**Constraint map components**	**Variables influencing transition according to stakeholders**	**Variables influencing transition according to literature**
Built up 0.0074	Deciduous open forest – 2 Herbaceous vegetation -1	Shrubland, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown Forest (closed) evergreen broadleaved forest (open), unknown Forest (open) Sea	High population increase (use distance from settlements)	Distance from roads, slope, distance from sea
Cropland 0.4095	Shrubland – 1 Deciduous open forest – 3	herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), unknown forest (open), sea	Proximity to Pujini	Distance from existing cropland, distance from evergreen forest, distance from closed forest, distance from built up, distance from roads, slope
Unknown forest closed 0.0938	Shrubland - 1	Herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), Sea	-	Distance from built up, distance from roads, slope

Table 24. Fuzzy operation details for the decision variables influencing the spatial allocation of three land cover transitions outlined in scenario two (ecosystem management) for Pemba; T1 – to built up, T2- to cropland, T3 – unknown forest.

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T1	Distance from sea	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T1	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79
T1	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T2	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T2	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T2	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79
T2	Distance from evergreen forest (closed)	Monotonically decreasing	Sigmoidal	c. 0.01; d. 0.03
T2	Distance from closed forest (all)	Monotonically decreasing	Sigmoidal	c. 0.00; d. 001
T2	Distance from Pujini	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.03
T3	Distance from built up	Monotonically increasing	Sigmoidal	a. 0.02; b. 0.03
T3	Distance from roads	Monotonically increasing	Sigmoidal	a. 0.02; b. 0.03
T3	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79

Table 25. Multi-criterion evaluation (MCE) weights Pemba scenario two, transition one.

Fuzzy output	Weight
Distance from roads	0.2234
Distance from sea	0.2867
Distance from built up	0.3943
Slope	0.0956

Table 26. Multi-criterion evaluation (MCE) weights Pemba scenario two, transition two.

Fuzzy output	Weight
Distance from built up	0.2109
Distance from evergreen forests	0.0739
Distance from roads	0.2379
Distance from closed forests	0.0909
Slope	0.0431
Distance from Pujini	0.3433

Table 27. Multi-criterion evaluation (MCE) weights Pemba scenario two, transition three.

Fuzzy output	Weight
Distance from built up	0.4545
Distance from roads	0.4545
Slope	0.0909

The same wetland transition that was applied to scenario one was also applied to this land cover map.

Unguja scenario 2 ecosystem management

Table 28. Modelling conditions for the ecosystem management scenario in Unguja. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	Take from land classes (likelihood 0-4)	Constraint map components	Variables influencing transition according to stakeholders	Variables influencing transition according to literature
Built up 0.03348	Cropland – 1 Unknown forest (open) – 2 Herbaceous vegetation – 2	Shrubland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), sea	Close proximity to Muyuni (use Kigomani as understands they refer to Muyuni beach and on the county map Muyuni shows as a different district), Paje and Kiwengwa	Distance from roads, slope, distance from sea
Bare sparse vegetation 0.0019	Unknown forest closed – 1	Shrubland, herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, Evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	-	Distance from settlements, distance from roads, distance from evergreen forests, distance from unknown forests, distance from shrubland, slope
Unknown 0.092	Cropland – 4	Shrubland, herbaceous vegetation, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	-	Distance from existing cropland, distance from built up, distance from roads, slope
Deciduous forest (open) 0.099	Shrubland – 2	Herbaceous vegetation, Cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	Close proximity to Pongwe	Distance from built up, distance from roads, distance from deciduous forest

Table 29. Fuzzy operation details for the decision variables influencing the spatial allocation of four land cover transitions outlined in scenario two (ecosystem management) for Unguja; T1 – to built up, T2- to bare or sparse vegetation, T3 – unknown forest, to deciduous forest (open)

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from Kigomani	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T1	Distance from Kiwengwa	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T1	Distance from Paje	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T1	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.01
T1	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T1	Distance from sea	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T1	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.01; d. 0.03
T2	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.01; d. 0.03
T2	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.01
T2	Distance from evergreen forests	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T2	Distance from unknown forests	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T2	Distance from shrubland	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T2	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T3	Distance from cropland	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.02
T3	Distance from built up	Monotonically increasing	Sigmoidal	a. 0.01; b. 0.03
T3	Distance from roads	Monotonically increasing	Sigmoidal	a. 0.00; b. 0.02
T3	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T4	Distance from Pongwe	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T4	Distance from built up	Monotonically increasing	Sigmoidal	a. 0.01; b. 0.03
T4	Distance from roads	Monotonically increasing	Sigmoidal	a. 0.00; b. 0.02
T4	Distance from deciduous forest	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.02

Table 30. Multi-criterion evaluation (MCE) weights Unguja scenario two, transition one.

Fuzzy output	Weight
Distance from roads	0.0785
Distance from build up	0.1592
Distance from sea	0.1206
Slope	0.1793
Distance from Kigomani	0.1541
Distance from Kiwengwa	0.1541
Distance from Paje	0.1541

Table 31. Multi-criterion evaluation (MCE) weights Unguja scenario two, transition two

Fuzzy output	Weight
Distance from shrubland	0.2967
Distance from roads	0.0959
Distance from built up	0.0606
Slope	0.2577
Distance from unknown forest	0.1445
Distance from evergreen forest	0.1445

Table 32. Multi-criterion evaluation (MCE) weights Unguja scenario two, transition three.

Fuzzy output	Weight
Distance from cropland	0.3000
Distance from roads	0.3000
Distance from built up	0.3000
Slope	0.1000

Table 33. Multi-criterion evaluation (MCE) weights Unguja scenario two, transition four.

Fuzzy output	Weight
Distance from deciduous forest	0.0672
Distance from roads	0.1538
Distance from built up	0.1698
Distance from Pongwe	0.6092

The same additional wetland transition applied to the first scenario was also applied to this land cover map.

Pemba scenario 3 - settlement planning

Table 34. Modelling conditions for the settlement planning scenario in Pemba. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	Take from land classes (likelihood 0-4)	Constraint map components	Variables influencing transition according to stakeholders	Variables influencing transition according to literature
Deciduous forest 0.3302	Evergreen forest - 2	Shrubland, herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, deciduous broadleaved forest (closed), unknown forest (closed), deciduous broadleaved forest (open), unknown forest (open), sea	Close to built up areas, close to existing forest (closed)	Distance from roads, slope
Bare sparse vegetation 0.137	Herbaceous vegetation - 3	Shrubland, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed) evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	-	Distance from built up, distance from roads, distance from forests (closed)
Herbaceous wetland 2.256	Unknown forest - 2	Shrubland, herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), sea	Low slope close to the sea	Distance from built up, distance from roads

Table 35. Fuzzy operation details for the decision variables influencing the spatial allocation of four land cover transitions outlined in scenario two (ecosystem management) for Unguja; T1 – to deciduous forest, T2- to bare or sparse vegetation, T3 – herbaceous wetland.

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T1	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79
T1	Distance from closed forest	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.001
T1	Distance from settlements	Monotonically decreasing	Sigmoidal	c. 0.0001; d. 0.001
T2	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T2	Distance from closed forest	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.001
T2	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T2	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79
T3	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T3	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.02; d. 0.03
T3	Slope	Monotonically decreasing	Sigmoidal	c. 5.9; d. 11.79
T3	Distance from sea	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.002

Table 36. Multi-criterion evaluation (MCE) weights Pemba scenario three, transition 1.

Fuzzy output	Weight
Distance from roads	0.2563
Slope	0.2767
Distance from closed forest	0.2440
Distance from settlements	0.2230

Table 37. Multi-criterion evaluation (MCE) weights Pemba scenario three, transition two.

Fuzzy output	Weight
Distance from built up	0.2403
Distance from closed forest	0.2231
Distance from roads	0.4472
Slope	0.0894

Table 38. Multi-criterion evaluation (MCE) weights Pemba scenario three, transition three.

Fuzzy output	Weight
Distance from built up	0.0691
Distance from roads	0.0769
Slope	0.2937
Distance from sea	0.604

For this scenario the prediction for transition 3 was that some land would be lost to sea. Instead of doing a direct loss of land to sea a transition was instead made to wetland as this appeared to be the prediction associated with sea level rise from the BAU scenario. Because in the prediction the percentage of land loss to the sea was not calculated the number of pixels associated with the wetland transition in the earlier BAU model was taken and used to model this transition.

As a transition to wetland was modelled at this stage the additional wetland transition was not needed.

Unguja scenario 3 settlement planning

Table 39. Modelling conditions for the settlement planning scenario in Unguja. Likelihood of land transition ranges from 1 (least likely) to 4 (most likely). Relationship of the influencing variables to the pattern of transition described as monotonically increasing (the further away from the variable the more likely the transition), monotonically decreasing (the further away the variable is the less likely the transition).

Land class increase in demand (ha)	**Take from land classes (likelihood 0-4)**	**Constraint map components**	**Variables influencing transition according to stakeholders**	**Variables influencing transition according to literature**
Built up 0.024	Cropland – 3 Unknown forest - 3	Shrubland, herbaceous vegetation, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, Evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), evergreen broadleaved forest (open), deciduous broadleaved forest (open), sea	Areas close to built up areas, areas close to roads, distance from Ukongoroni, on Tambatu island	Distance from cropland, distance from unknown forest, slope
Bare sparse vegetation 0.0015	Shrubland - 2	Herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, Evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed) evergreen broadleaved forest (open), deciduous broadleaved forest (open), unknown forest (open), sea	Distance from Kiwengwa	Distance from built up, distance from roads, distance from existing shrubland, slope
Shrubland 0.1572	Deciduous forest (open) – 3 Evergreen forest (open) - 3	Shrubland, herbaceous vegetation, cropland, built up, bare or sparse vegetation, permanent waterbodies, herbaceous wetland, Evergreen broadleaved forest (closed), deciduous broadleaved forest (closed), unknown forest (closed), unknown forest (open), sea	Distance from Mtule	Distance from built up, distance from roads, distance from existing shrubland, slope

Table 40. Fuzzy operation details for the decision variables influencing the spatial allocation of three land cover transitions outlined in scenario three (settlement planning) for Unguja; T1 – to built up, T2- to bare or sparse vegetation, T3 – to shrubland.

Transition	Variable name	Function shape	Function type	Control points
T1	Distance from cropland	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.002
T1	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T1	Distance from unknown forests	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T1	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.01
T1	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.01; d. 0.02
T1	Distance fromTambatu island	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T1	Distance from Ukong	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T2	Distance from Kiwengwa	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T2	Distance from shrubland	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T2	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.01
T2	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.01; 0.02
T2	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T3	Distance from Mtule	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.04
T3	Distance from shrubland	Monotonically decreasing	Sigmoidal	c. 0.00; d. 0.01
T3	Distance from roads	Monotonically decreasing	Sigmoidal	c. 0.001; d. 0.01
T3	Slope	Monotonically decreasing	Sigmoidal	c. 0.74; d. 3.69
T3	Distance from built up	Monotonically decreasing	Sigmoidal	c. 0.01; d. 0.02

Table 41. Multi-criterion evaluation (MCE) weights Unguja scenario three, transition 1.

Fuzzy output	Weight
Distance from cropland	0.0434
Slope	0.0240
Distance from unknown forest	0.0287
Distance from roads	0.2039
Distance from built up	0.2158
Distance from Tambatu island	0.2421
Distance from Ukongoroni	0.2421

Table 42. Multi-criterion evaluation (MCE) weights Unguja scenario three, transition 2.

Fuzzy output	Weight
Slope	0.0331
Distance from built up	0.2936
Distance from roads	0.2936
Distance from shrubland	0.0528
Distance from Kiwengwa	0.3269

Table 43. Multi-criterion evaluation (MCE) weights Unguja scenario three, transition 3.

Fuzzy output	Weight
Distance from Mtule	0.3505
Distance from shrubland	0.0408
Distance from roads	0.2956
Slope	0.1695
Distance from built up	0.1437

7. Results full land cover classes before simplification

Table 44. Percentage differences in land cover area between the present day actual land cover and the predicted values for the BAU scenario for 2030 in Pemba.

	Area 2019 (ha)	**Area 2030 BAU (ha)**	**Difference 2019 and BAU (%)**	**Area 2030 S1 (ha)**	**Difference 2019 and S1 (%)**	**Area 2030 S2 (ha)**	**Difference 2019 and S2 (ha)**	**Area 2030 S3 (ha)**	**Difference 2019 and S3 (%)**
Shrubland	0.524	0.563	3.59	0.546	4.19	0.131	-60.12	0.524	0.03
Herbaceous vegetation	1.195	0.585	-34.27	1.006	-17.2	0.976	-10.07	1.058	-6.08
Cropland	1.365	1.72	11.51	1.534	11.69	1.775	13.05	1.365	0.01
Built up	0.833	0.87	2.16	0.851	2.17	0.841	0.45	0.833	0.01
Bare or sparse vegetation	0.003	0.006	39.12	0.006	59.32	0.003	-7.51	0.140	95.80
Permanent waterbodies	0.4	0.033	-84.85	0.23	-54.11	0.23	-27.06	0.400	0.04
Herbaceous wetland	4.755	8.919	30.45	5.448	13.58	5.448	6.79	5.448	6.79
Evergreen broadleaved forest (closed)	0.601	0.601	-0.03	0.6	-0.12	0.601	0	0.272	-37.61
Deciduous broadleaved forest (closed)	0.978	0.975	-0.15	0.975	-0.29	0.978	-0.01	1.308	14.44
Unknown forest (closed)	7.394	5.518	-14.53	7.214	-2.46	7.3	-0.64	7.165	-1.58
Evergreen broadleaved forest (open)	0.003	0.003	0	0.003	-1.715	0.003	-0.86	0.001	-46.13
Deciduous broadleaved forest (open)	0.038	0.038	0	0.037	-2.04	0.014	-47.18	0.038	-0.53
Unknown forest (open)	13.465	11.704	-6.99	13.104	-2.72	13.257	-0.78	13.002	-1.75
Sea	66.069	66.595	0.4	66.069	0	66.069	0	66.069	0.00
No data	0.524	0.563	7.18	0.506	-0.53	0.506	-1.77	0.506	-1.75

Table 45. Percentage differences in land cover area between the present day actual land cover and the predicted values for the BAU scenario for 2030 in Unguja.

	Area 2019 (ha)	**Area 2030 BAU (ha)**	**Difference 2019 and BAU (%)**	**Area 2030 S1 (ha)**	**Percentage difference 2019 and S1**	**Area 2030 S2 (ha)**	**Difference 2019 and S2**	**Area 2030 S3 (ha)**	**Difference 2019 and S3**
Shrubland	1.074	0.335	-52.43	0.722	-39.22	0.689	-21.87	0.831	-12.75
Herbaceous vegetation	1.439	1.434	-0.17	1.322	-8.46	1.165	-10.53	1.175	-10.12
Cropland	1.116	1.113	-0.15	1.033	-7.7	0.986	-6.18	1.029	-4.06
Built up	2.254	2.381	2.74	2.358	4.5	2.370	2.51	2.368	2.46
Bare or sparse vegetation	0.038	0.038	0	0.022	-51.43	0.024	-22.11	0.024	-23.46
Permanent waterbodies	0.364	0.083	-62.97	0.33	-9.75	0.237	-21.09	0.238	-20.98
Herbaceous wetland	3.462	8.443	41.84	4.22	19.72	5.027	18.44	5.049	18.64
Evergreen broadleaved forest (closed)	0.516	0.514	-0.18	0.816	45.09	0.515	-0.12	0.516	0.00
Deciduous broadleaved forest (closed)	3.097	3.085	-0.18	3.089	-0.24	3.087	-0.16	3.095	-0.04
Unknown forest (closed)	19.12	16.997	-5.88	18.706	-2.19	18.773	-0.91	18.722	-1.05
Deciduous broadleaved forest (open)	0.099	0.098	-0.19	0.099	-0.35	0.155	22.04	0.007	-87.45
Unknown forest (open)	16.704	14.761	-6.17	16.245	-2.79	16.140	-1.72	16.231	-1.44
No data	0	0	0	0.32		0	0	0	

8. Consolidation of land classes

Because the transitions in some cases were small, and the fact that results are based on subjective qualitative descriptions, it was felt that overly detailed land cover classes might suggest more accurate knowledge on transitions than is presented. To really understand how land cover transitions might broadly impact land cover types which support water-energy-food security it is more useful to look at some of the potential broader transitions. For that reason, the land cover classes were consolidated. Please see below:

Table 46. Details of land cover consolidation for final map images and calculations.

New class	Old class
Shrubland	Shrubland, Herbaceous wetland
Cropland	Cropland
Built up	Built up
Bare sparse vegetation	Bare sparse vegetation
Permanent waterbodies	Permanent waterbodies
Forested wetland	Herbaceous vegetation
Natural forests	Evergreen forests (open and closed) Unknown forests (open and closed)
Plantation forest	Deciduous forests (open and closed)
Sea	Sea