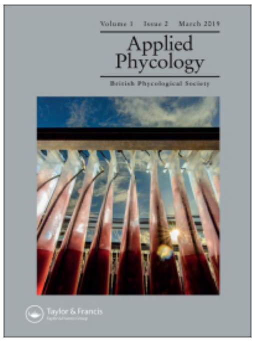

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A resilience lens to explore seaweed farmers' responses to the impacts of climate change in Tanzania

Ivy Matoju[a], Virginie Le Masson[b], Valeria Montalescot[c], Msafiri Andrew Ndawala[a] and Flower E. Msuya[a]

[a]Botany Department, University of Dar es Salaam, Dar es Salaam, Tanzania; [b]IRDR Centre for Gender and Disaster, University College London, London, UK; [c]Scottish Association for Marine Science, SAMS, Oban, UK

ABSTRACT
Seaweed-based mariculture is an important source of livelihoods for impoverished coastal communities in Tanzania. However, the impacts of climate change across East Africa are putting a strain on the growth of the seaweed industry. Smallholder farmers are already mobilizing strategies to cope with challenges such as disease outbreaks, but they are struggling to maintain seaweed production and derive sufficient income. A better understanding of the challenges they face and the factors inhibiting their ability to build resilience is needed to inform policies and development programmes to achieve the Sustainable Development Goals, particularly Goal 13 on Climate action and Goal 14 on Life Below Water. The global demand for seaweed is expanding rapidly. Strengthening the adaptability of seaweed production to climate change is important for farmers to rely on it as a source of livelihoods on which they can build their own resilience to climate change. Drawing on qualitative data from key informant interviews in four Tanzanian seaweed-producing areas, this paper assesses the long-term resilience capacities of seaweed farmers to respond to one of the main hazards: diseases affecting seaweed crops. While several strategies help farmers maintain their income, most of them only support resilience in the short term. The increasing pressure on marine resources and the lack of regulations for supporting an equitable and sustainable seaweed-based mariculture sector do not bode well for farmers' long-term adaptation to climate change and environmental degradation. Seaweed farming remains a crucial source of livelihoods for poor coastal communities in Tanzania, but it does not currently lead to positive transformative changes in their socio-economic conditions. Policies aiming to support sustainable aquaculture, particularly in tropical ecosystems that are highly vulnerable to climate change, must address the existing social, economic and knowledge inequities that prevent poor communities from building their resilience.

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Aquaculture; climate change; resilience; seaweed farming; Tanzania

Introduction

Seaweed farming is among the fastest growing sectors in aquaculture (Fisheries, 2018). Seaweeds are mainly produced for human consumption and to make hydrocolloids used as food additives and in high-value markets like cosmetics and pharmaceuticals (McHugh, 2003, Pegasus guidelines, 2019). Carrageenan and agar are the two main seaweed-based hydrocolloids: commercial interest and market demand have enhanced the production of red seaweeds in tropical waters – *Kappaphycus* and *Eucheuma* (known collectively as eucheumatoids) for carrageenan production and *Gracilaria* for agar production (Msuya, 2020).

The Tanzanian seaweed industry is based on cultivation and small-scale processing of eucheumatoids. In 1989, imported seaweeds from the Philippines began to replace native species as *Eucheuma* (locally known as "spinosum") and *Kappaphycus* (locally known as "cottonii") began to be commercially cultivated in the Zanzibar Islands (Lirasan & Twide, 1993; Mshigeni, 1998; Msuya et al., 2014). The rapid expansion of seaweed farming in the Zanzibar Islands had a significant impact on the livelihoods of coastal communities, providing employment and income for some of the most marginalized, particularly women (Msuya, 2006, 2012). Although equal numbers of men and women were initially involved in seaweed cultivation, a current feature of the Tanzanian seaweed industry is the high number of women farmers (Msuya, 2006; Neish & Msuya, 2013). Stakeholders in the seaweed value chain range across different age groups, with young people increasingly involved (Msuya, 2013).

Tanzania does not produce carrageenan locally: its seaweeds are cultivated, harvested and dried before being sold to exporters for carrageenan extraction abroad. This is unlike the two main producers of

CONTACT Virginie Le Masson v.lemasson@ucl.ac.uk
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eucheumatoids, the Philippines and Indonesia, where carrageenan extraction and refining are generally done in-country. The fact that downstream processing for carrageenan extraction happens entirely outside Tanzania leaves Tanzanian farmers dependent on the price paid by exporters, which fluctuates depending on world market prices. To try and add value to produced seaweed and therefore stabilize and diversify incomes, local initiatives such as the Zanzibar Seaweed Cluster Initiative have supported and trained farmers to produce seaweed-based soaps, body creams and food products (Msuya, 2013). However, these are produced in small volumes and with a small proportion of seaweed in their formulations, so their ability to expand local markets has been minimal (Neish & Msuya, 2013).

The Seaweed Development Strategic Plan of 2005 (Nanyaro, 2005) and several studies of the seaweed value chain in Tanzania (Christophe, 2015; Neish & Msuya, 2013; Shimba, Magombola, & Ibrahim, 2021; Songwe, Khamis, Khalfan, & Msuya, 2016) have identified recurring challenges faced by stakeholders involved in the seaweed industry. These challenges are summarized below according to three geographical scales pertaining to aquaculture systems: farm scale, aquaculture zone and global scale (Soto, Aguilar-Manjarrez, & Hishamunda, 2008).

At the *farm scale*, farmers face biological hazards in the form of increased disease outbreaks. These are exacerbated by the low quality of planting materials, poor farming methods and biosecurity issues such as pest and disease infestation (Msuya, 2011). Farmers cultivate germplasms from the *Eucheuma* and *Kappaphycus* genera, mainly from the Philippines, which are of limited genetic diversity (Msuya, 2006). Indeed, the global expansion of the current commercial cultivars relies on the successive introduction of few haplotypes, and this might have caused the spread of non-native pests and diseases. Furthermore, this limited genetic variation at the origin, added to continuous propagation using the same seed, increases vulnerability to diseases and pests such as ice-ice syndrome and epiphytes (Brakel et al., 2021), which are leading concerns for farmers (Msuya, 2011; Msuya & Porter, 2014). Farmers increased cultivation of “spinosum” which they deemed more resistant (Msuya, 2006), but this has a lower value than “cottonii”, and its production is now declining (Rusekwa, Campbell, Msuya, Buriyo, & Cottier-Cook, 2020).

At the scale of the *aquaculture zone or watershed*, seaweed farmers increasingly face environmental hazards and stresses such as increased water temperatures (Hayashi, Hurtado, Msuya, Bleicher-Lhonneur, & Critchley, 2010; Msuya, 2011; Msuya & Porter, 2014), which negatively affect yields (Ateweberhan, Rougier, & Rakotomahazo, 2015). In many cultivation sites, seaweed farming is failing in the shallow intertidal areas where it used to grow well (Msuya & Porter, 2014). Ideal environmental conditions for seaweed cultivation include temperatures of 24–30°C and flowing water that allows for nutrient transfer. However, since the 1950s, average sea-level temperatures in the Indian Ocean have risen by 1°C and average air temperatures by 1°C, while annual rainfall has decreased by 3.3% (Climate Links, 2012, 2018), and there has been an overall increase in the frequency and intensity of heatwaves (FCFA, 2017). These environmental changes have implications for mariculture-related activities, management practice, decisions and policies.

At the *global* scale, the “spinosum” variety produced in Tanzania competes with that from other exporting countries such as the Philippines and Indonesia who produce other varieties in high quantities while benefiting from lower shipping costs to markets in China, South America and the USA (Neish & Msuya, 2013).

Several studies have raised concerns over the decline in the initial socio-economic benefits of seaweed farming for coastal communities (Bryceson, 2002; Fröcklin, de la Torre-Castro, Lindström, Jiddawi, & Msuya, 2012; Shimba et al., 2021). These concerns are exacerbated by increased biological and environmental hazards and the limited prospects for large-scale downstream activities in the Tanzanian seaweed value chain. In light of the above challenges, we ask whether and how seaweed farming could remain a sustainable source of income for coastal communities in Tanzania. We do this by applying the concept of resilience to seaweed farming, focusing on the lived experiences of seaweed farmers to understand how they cope with the multiple local and global pressures on their main livelihood and to generate insights into their capacities to remain resilient to multiple overlapping risks.

Applying the concept of resilience to seaweed farming

Our focus on seaweed farmers’ strategies for coping and responding to risks affecting their natural resources aims to contribute to the body of knowledge that views aquaculture as an interconnection of physical, ecological, social and economic systems influencing the development of coastal communities (Adger, 2000; Ateweberhan et al., 2015, 2018; Mirera, 2014; Suckall, Tompkins, & Stringer, 2014; Wetengere, 2009). The Ecosystem Approach to Aquaculture (EAA) in particular (Soto et al., 2008) encourages the examination of its socio-ecological aspects in an integrated manner to support sustainability, resilience and equity (Brugère, Aguilar-Manjarrez, Beveridge, & Soto, 2018). In this paper, we use the concept of resilience to explore how seaweed farmers respond to challenges and new risks.

Drawing on how the EAA approach encapsulates resilience, we recognize that aquaculture systems can sustain a certain degree of change up to a point (Brugère et al., 2018). Within this, the resilience lens applied in this study draws on conceptualizations from the literature on disaster risk reduction, in particular on the framework of resilience capacities developed by Manyena, Machingura & O'Keefe (2019) and summarized in Table 1. Based on this framework, the analysis of resilience relies on both the assessment of the risk context and the way populations respond to risks.

First, assessing the key risk drivers (resilience to what?) and identifying the people likely to be affected by shocks and stresses (whose resilience?) help to draw a picture of the risk context through three aspects: (i) *Hazards* of both natural (e.g., a storm) and anthropogenic origins (e.g., pollution); (ii) *Exposure*, including information such as the number of people who rely on seaweed farming for a significant proportion of their livelihoods or the type of infrastructure they rely on, which can help better understand people's exposure to risks; and (iii) *Vulnerability*, i.e., physical, socio-economic, political and cultural factors that help explain why certain people are more at risk than others. For instance, due to gender inequalities, women, globally, tend to spend a disproportionate amount of time on unpaid domestic chores, which often limits their economic income and therefore their financial resources (Rao, Lawson, Raditloaneng, Solomon, & Angula, 2019).

Table 1. Resilience capacities, adapted from Manyena et al. (2019).

Resilience capacities	Definitions
Preventive capacities	All corrective and prospective activities that support development outcomes, improve people's living standards and reduce their vulnerability.
Anticipative capacities	The extent to which people understand risks and disaster scenario, access information and implement actions in advance to avoid or reduce the risks and prepare for effective response.
Absorptive capacities	Communities' abilities to cope or contain the effects of an extreme phenomenon through resisting to impacts and developing survival mechanisms.
Adaptive capacities	Accepting certain levels of risk and mobilizing strategies to moderate future damages such as by diversifying livelihoods or changing farming practices.
Transformative capacities	Strategies that challenge the status quo; people's capabilities to choose how to live differently and tackle some of the societal structures that determine their vulnerability.

Second, assessing people's response(s) to these risks (resilience through what action?) helps to better understand the capacities that they mobilize. Table 1 divides these capacities into five overlapping categories.

Finally, the assessments of both the risk context and people's set of capacities to respond allow for the analysis of resilience outcomes which can range from "bouncing back" to "bouncing forward". The bounce-back notion, predominant in long-established definitions of resilience in the fields of ecology or physics from the 1970s, refers to the abilities of a system to preserve and restore essential basic structures and functions. However, more recent conceptualizations of resilience in the fields of development studies, geography and disaster risk reduction have questioned the return to the status quo which may have led to disasters in the first place. As Manyena (2006) observes, communities which can mobilize capacities to transform their conditions and address some of the causes of their vulnerability strengthen their resilience by "bouncing forward". Based on this conceptual framework, the rest of this paper examines the resilience of farmers in four seaweed-producing regions in Tanzania.

Methodology

The multifaceted dimensions of resilience (ecological, economic, spatial, social and institutional) require an interdisciplinary understanding and analysis at various scales (Adger, 2000; Berkes & Folke, 1998; Folke, 2016). The present study resulted from a collaboration between researchers involved in a large interdisciplinary programme with four linked strands of work: disease and pest detection, biosecurity practices and policy, algal genetic resources and socio-economic resilience (see Fig 1).

This paper results from work undertaken in the fourth area of research but which benefitted from the insights of the rest of the programme. Researchers collected and analysed primary qualitative data in four locations in three distinct geographical regions of Tanzania (see Fig 2): Zanzibar (Unguja and Pemba islands), Mtwara and Lindi. Fieldwork took place between October 2018 and June 2019.

Three forms of data collection were used and triangulated: (i) secondary data, (ii) key informant interviews and (iii) the results of a Knowledge, Attitudes and Practices (KAP) survey, the latter conducted by colleagues working on the second objective of the project (see Fig 1).

First, secondary data from governmental reports and the scientific literature contributed to the assessment of the risk context in the seaweed-producing sites. Second,

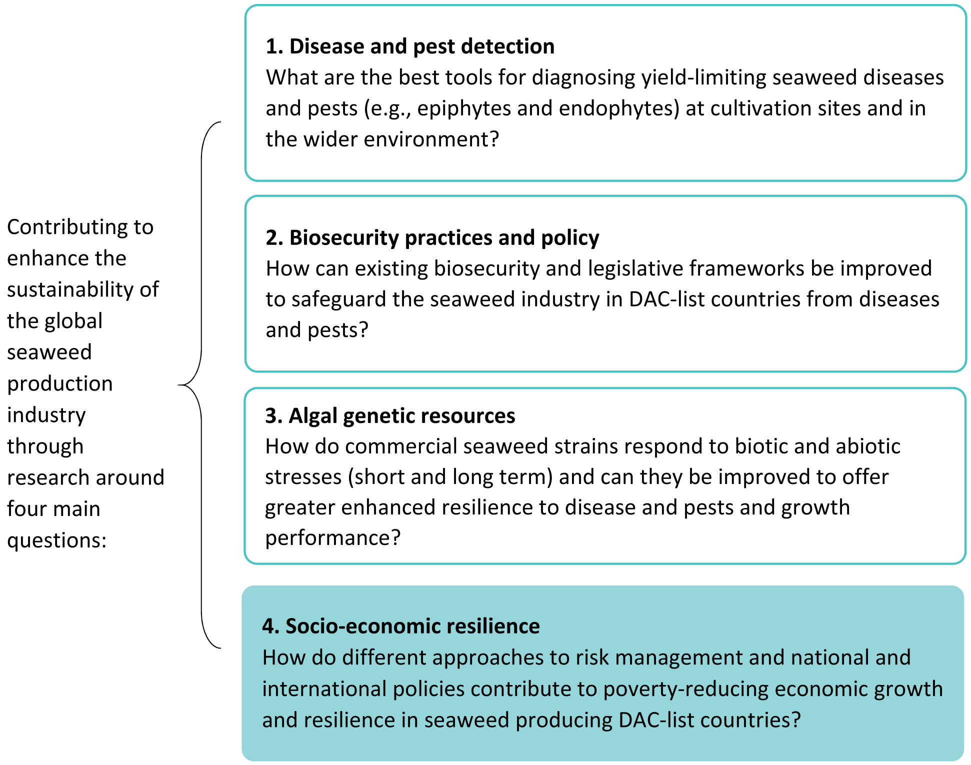

Figure 1. The four areas of research pursued by the global seaweed STAR programme.

87 Key Informant Interviews (KII) were conducted with farmers (n = 46; women = 31; men = 15), seaweed collectors or buyers (n = 12, all men), processors (n = 15, all women), exporters (n = 1 man) and local authorities (n = 13, all men). Semi-structured interviews focused on (i) seaweed farming practices and any gender differences in farming methods; (ii) challenges faced by farmers (environmental and socio-economic), (iii) trade-related issues, (iv) governance mechanisms and (v) plans and vision of local authorities involved in the seaweed value chain. The interviews aimed to obtain information at both production and institutional levels, particularly about the challenges farmers faced and the opportunities they seized to help them cope with difficulties. Interviews were complemented with visual observations of participants and notes based on data collected by other team members of different disciplines. This included observing farmers during their daily activities, the crops they harvested, the activities of buyers, the gender division of labour, the transport of seaweed to main hubs, the presence of exporting companies in the different sites and the fabrication and selling of seaweed-based products. Qualitative tools such as interviews and observation helped the team collect information about the lived experiences of different stakeholders working in seaweed aquaculture including farmers' unspoken behaviours and informal relationships. It also helped to draw insights into people's perceptions of risk, their needs and priorities and their strategies for coping with challenges. Data were transcribed and coded according to a set of themes identified collectively among team members to describe the factors that favour or hinder the resilience of seaweed farmers. Themes that were not pre-identified but which arose from the transcripts were included as well.

Third, the qualitative data obtained with the methodology described above were triangulated with the results from the KAP survey (Campbell et al., 2022) which was conducted in the same sites with 89 farmers. This enabled the team to verify facts about farming practices and strategies developed by seaweed farmers to cope with diseases.

The analysis relies on and follows the conceptual framework introduced above. It is divided into two parts: part 1 draws a picture of the risk context within which seaweed farmers live in Tanzania. It includes informants' perceptions of environmental shocks and stresses affecting seaweed farming, as well as quantitative secondary data from national-level population surveys to better understand seaweed farmers' exposure and vulnerability context. Part 2 analyses the set of strategies and capacities developed by farmers to respond to risks. This supports the subsequent discussion of the resilience outcomes for seaweed farming. To

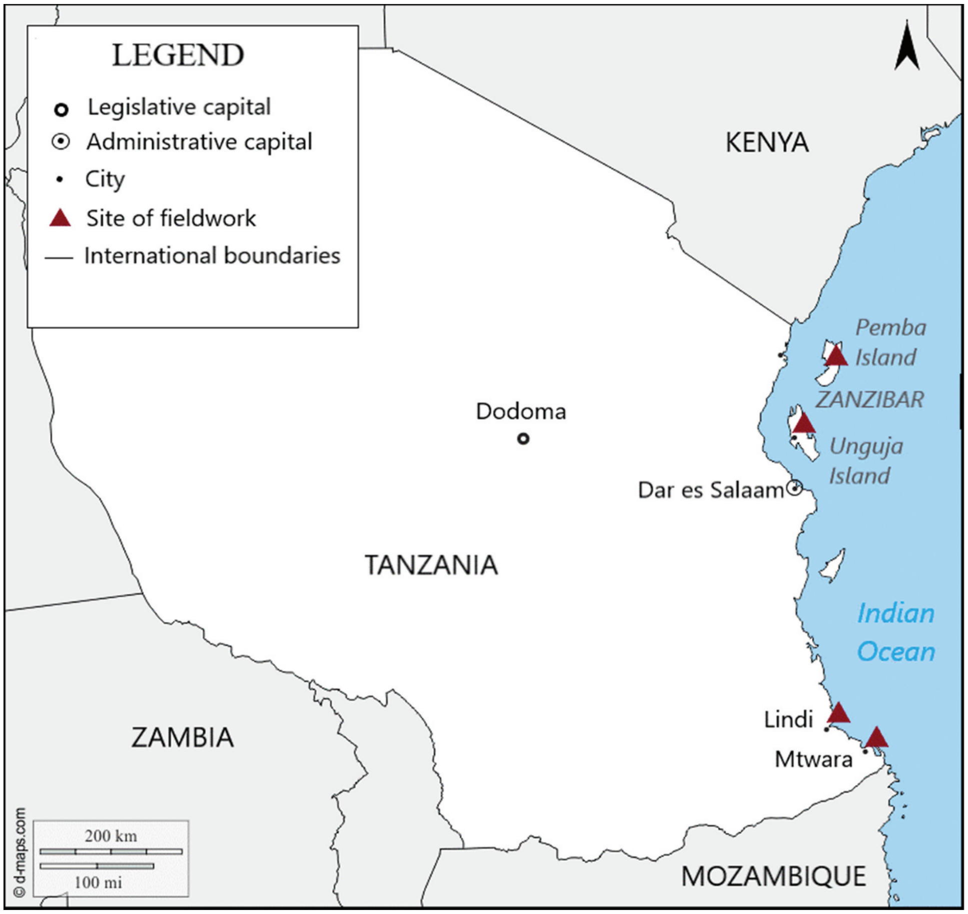

Figure 2. The map of Tanzania with the visited sites.

further encourage interdisciplinarity, the analysis was reviewed by team members from other disciplines during an online workshop. This discussed the interpretation of the data and the implications for research on socio-ecological resilience of seaweed farming in Tanzania.

Drivers of risks and capacities of seaweed farmers

Risk drivers

Hazards affecting seaweed production

The main challenge highlighted by farmers was how to avoid crop failure and loss. In all four locations, farmers stressed their concern with the occurrence of diseases and weather-related events affecting seaweed crops. Hot weather was reported across the four sites and noted to increase the occurrence of diseases. "[…] Especially this year, I have not harvested anything from my farm" – Farmer, woman, 36 years, Naumbu, Mtwara). While farmers in Mtwara and Unguja emphasized diseases as their main concern, those in Pemba and Lindi focused on weather-related challenges including strong monsoon winds and hot weather, perceived to increase sun intensity and seawater temperature. "Seaweed is greatly affected by diseases, not sure of the cause but others speculate it is due to high sun intensity and the seawater is warm" (Farmer, man, 37 years, Songo Songo, Lindi). Monsoon winds affect the farms located off the coast of mainland Tanzania by dislodging the pegs holding the ropes and leading to the breaking of seaweed at the anchor point between the *tai-tai* (nylon-based materials used to hold the seaweed to the line) and the ropes, resulting in crop loss. Informants observed that the northern monsoon winds (November to March) bring heat, while the southern monsoon winds are very strong (April to October).

In all four sites, farmers directly linked hazards mentioned above with climate change. Their observations of the occurrence of strong monsoon winds increased hot weather, and increased water temperature is consistent with the documented and projected impacts of climate change in Tanzania in the scientific literature. These include changes in wind speed, sea waves, more irregular rainfall patterns and changes in salinity levels

(Hassan & Othman, 2019). Mtwara-based informants highlighted two key changes: hot weather and the entry of freshwater into farms. They attributed these two impacts to climate change and the resulted reduction of production. Lindi-based farmers were more aware of changes in water temperature and the hot weather leading to crop decline. Additionally, Lindi and Mtwara informants mentioned the increasing strength of the monsoon winds as an impact of climate change. Unguja respondents pointed out climate change as the main risk that leads to the occurrences of seaweed diseases. This was echoed by respondents in Pemba who noted a significant difference in the growth rates between the cold and hot seasons and that rising water temperatures have led to disease outbreaks and lower yields at harvest, lowering their projected income: "During the rainy season, seaweed grows well with little disease but during the dry period seaweed is affected greatly with diseases" (Farmer, man, 46 years, Fundo Island, Pemba).

Farmers reported being affected by ice-ice disease (which presents on seaweed as a whitening and hardening of the thallus) and epiphytic pests (seaweeds of a different species that attach to cultivated seaweed): "Yes, I have experienced crop failure several times due to diseases perhaps due to high temperatures because during the rainy season when water temperature is low, seaweed disease is low" (Farmer, woman, 53 years, Jambiani, Unguja). Supplementary data from the KAP survey confirm that the effects of changing weather patterns can affect the growth cycle at least once a year through increased epiphytic infestation and disease outbreaks, and this has been noted by buyers in Pemba and Unguja: "Seaweed nowadays is really affected by diseases and therefore collecting enough seaweed for export takes a long time" (Exporter, man, Unguja) "Temperatures are high causing spoilage of seaweed at the farms before harvesting. We get less and less seaweed even though the number of farmers is increasing" – Buyer, man, Uzi, Unguja (see survey form in Supplementary materials).

Exposure: who and what is at risk?

In line with the conceptual framework, this section discusses exposure to risk in terms of the number of people farming seaweed and the type of farming infrastructure they use.

Seaweed constitutes a source of livelihoods for approximately 31,000 farmers in coastal communities in Tanzania (Rusekwa et al., 2020) and is an important income generator for those communities interviewed for this study. The seaweed industry scaled up steadily between 1990 and 2015, from 808 tonnes dry weight (dw) per year to 16000 tonnes dw (Msuya, 2020). This brought economic growth to coastal communities, particularly to women farmers who were able to generate an income and improve their living standards (Msuya, 2011; Msuya & Hurtado, 2017). The general opinion of the informants was that the income from seaweed has aided them in catering for their family needs: "Yes (it is profitable). I earn money which has helped me build a house, pay fees for my children and other family needs" (Farmer, man, Tumbe, Pemba). However, production began to decline after 2015, and in 2020, only 8967.1 tonnes were harvested in Zanzibar, worth 6223.3 million Tanzanian Shillings (US $2.7 million) (see Table 2).

Prices for both "cottonii" and "spinosum" vary between production sites. In Unguja, clean dried seaweed can be sold for up to TZS 800 per kg, while in other areas, the price drops to TZS 600 per kg. On average, a farmer can earn TZS 600 (~US $0.26) per kilogram of clean dried seaweed though this varies between TZS 600 and TZS 1000 (US $0.26–0.4) per kilogram for "spinosum" and "cottonii", respectively. The average prices for both "cottonii" and "spinosum" have fluctuated in recent years: disaggregated figures from the Ministry of Agriculture, Natural Resource, Livestock and Fisheries (RGoZ, 2018) attribute this to the steep increase in value of the "cottonii" species and the irregular increase in its production since 2016. These fluctuations continue a longer-term trend: in Songo

Table 2. Quantity and value of seaweed crops produced from 2016 to 2020 in Zanzibar.

Year	Quantity (tonnes)	Value (TZS)	Average price per kilogram for "cottonii" (1–2% of seaweed production) (TZS/kg^{-1})	Average price per kilogram for "spinosum" (>98% of seaweed production)(TZS/kg^{-1})
2015	16,724	9468.50 million	Not recorded	Not recorded
2016	11,229	4933.90 million	Not recorded	Not recorded
2017	10,981	4417 million	1358	400
2018	10,424.90	4358.80 million	1140	418
2019	9663.20	5667.60 million	Not recorded	685.3
2020	8967.10	6223.30 million	2372	679

Adapted from RGoZ (2017, 2018, 2019, 2020).

Songo Island, for example, production plummeted from 423.9 tonnes dw in 2003 to 26 tonnes dw in 2008 (Msuya & Porter, 2014).

Price volatility and the reduction in production volumes expose the community to economic risks which are enhanced by the risks to the seaweed infrastructure. In all four sites, most farmers use off-bottom techniques in shallow waters with pegs and lines. Seaweed cuttings (a technique also referred to as vegetative propagation) are attached to a rope with the help of "tai-tai", with the rope stretched between two poles made from mangrove or land-based wood that are anchored in the seabed. The location of seaweed farms in shallow waters directly exposes them to hot spells and increasing sea temperatures. Incidents of algal blooms have also been observed in Zanzibar, killing off *Eucheuma* seaweed species and affecting farmers' skin (Msuya, 2013a). Algal blooms are suspected to be linked to pollution and soil erosion that increases the nutrient load in seawater, combined with increased sea surface temperatures (Ateweberhan et al., 2015). In addition, seaweed farms located in coastal tropical ecosystems can be subjected to extreme weather phenomena such as cyclones and El Niño/Southern Oscillation (ENSO) events (Sallema & Mtui, 2008).

Tanzanian coasts are also increasingly exposed to environmental degradation. In Zanzibar, rapid population growth, settlement expansion and infrastructural developments for transportation and tourism are intensifying pressures on the environment, particularly in Unguja (Khamis, Kalliola, & Käyhkö, 2017). Such pressures lead to declining fish stocks and catch, shortage of mariculture products and ecological degradation including coral bleaching (ibid). Fishing practices such as the use of dynamite also damage coral reefs, in some cases irreparably (Tanzania Coastal Management, 2001). The nylon "tai-tais" seaweed farmers use contribute to water pollution when the plants are shaken loose from the ropes. Additionally, some mangrove forests in Unguja have been seriously degraded by harvesting for pegs for seaweed production (Othman, 2014). The infrastructure of seaweed farms is thus exposed to the impacts of climate change due to their location in tropical ecosystems but also to environmental degradation generated by socio-economic activities in attractive coastal areas, particularly in Zanzibar.

Vulnerability context

Assessing the vulnerability of seaweed farmers (their propensity to suffer from the impacts of climate change and other hazards) requires analysis of their socio-economic status and the broader societal context in which they live. Both will influence the resources farmers can or cannot access to protect themselves and their livelihoods and, therefore, enhance their resilience.

Approximately 80% of Tanzania's seaweed farmers are found in Zanzibar, particularly in the north of Pemba Island (Msuya, 2020; Neish & Msuya, 2013). The Zanzibar tourism industry provides for higher levels of off-farm employment than coastal areas on the mainland, which is reflected in the indicators on employment, occupations and education (Table 3). In all four sites, a high proportion of residents work in agriculture, except in Unguja where more men work in skilled manual jobs and more women work as unskilled labourers. In all four areas, more women are unemployed than men. In terms of household wealth (an

Table 3. Selected indicators on employment, occupation and education for women and men aged [15–49] by site (sources: EDS-MIS, 2015-16).

	Southern zone		Zanzibar	
	Lindi	Mtwara	Unguja	Pemba
Occupation				
% of women working in agriculture	72.7	67.5	12.5	39.1
% of men working in agriculture	73.4	58.1	26.4	42.5
% of women not employed in the 12 months preceding the survey	11.4	14.1	37.9	53.9
% of men not employed in the 12 months preceding the survey	2.2	5	17.7	17.8
Education				
% of women having completed grade 4 at the secondary level or went on to higher education	13.4	13.5	72.2	49.5
% of men having completed grade 4 at the secondary level or went on to higher education	14.7	17.7	69.4	52.5
Literacy				
% of literate women	68.2	71.7	91	75.6
% of literate men	75.4	82.2	94.5	83.8
Wealth quintile (%)				
Lowest	17.8	18.7	0.3	1.6
Second	30.4	29.9	1.5	15.4
Middle	26.1	24.8	8.6	25.3
Fourth	16.5	15	30.5	36.3
Highest	9.1	11.5	59.2	21.5
Gini coefficient	0.47	0.54	0.31	0.54

indication of people's access to services), there are significant differences between the two sites on Zanzibar and the two on the mainland. In Pemba and Unguja, over 70% of residents are in the highest wealth quintile, but fewer than 30% in Lindi and Mtwara.

Despite differences between four sites, particularly between Zanzibar and the southern sites on the mainland, two common factors of vulnerability can be identified. The first is that people who work in agriculture (including seaweed farmers) belong to the poorest households in the country and tend not to have completed primary school or any formal education at all (DHS-MIS 2015–16; see Supplementary tables S1 and S2). On average, households in the lowest quintiles are less likely to own consumer goods or access services that would improve their living standards compared to households in the higher quintiles.

Accounts from interviews with seaweed farmers nuanced this point: most declared that they were able to access basic services, and even if almost 50% of them did not receive a formal education, they had been able to improve their housing structures (from mud houses to bricks) and to pay school fees. One woman farmer in Songo Songo (Lindi) said that she was "currently building a house from generated income". Interviewees also confirmed that they had access to clean water, electricity and sanitation: while only 21% of the population of the mainland had access to electricity in 2015, by 2019 55% of Zanzibar inhabitants were connected to the grid (RGoZ, 2020a; OCGS, 2020), reflecting the islands' popularity as a tourism destination.

The second issue affecting vulnerability is gender. Most seaweed farmers in Tanzania are women (Neish & Msuya, 2013): when seaweed farming became a high-earning activity, it also attracted men (Besta, 2013), but the sector remains dominated by women. The gender of farmers matters because understanding some of the constraints women face helps understand which resources they might or might not be able to access. Overall, 64% of women who work in the agricultural sector in Tanzania are not paid and 78% work seasonally (EDS-MIS, 2015). Female-headed households, which represent 23% of households across Zanzibar, have less access to sanitation and electricity than male-headed households (ibid).

Particularly in Lindi and Mtwara, women were less likely than men to have any secondary schooling, which limits opportunities for employment. Recent figures for Zanzibar suggest that more girls than boys were enrolled in primary and secondary schools in 2019, but many more men (900) than women (391) were enrolled in technical and vocational skills training centres [Office of the Chief Government Statistician (OCGS), 2020]. Despite the relative equal access to education in Zanzibar, more men (55.7%) than women (44.3%) are formal employees in Zanzibar (RGoZ, 2019a) and more men are likely to work as skilled manual labour (Table 3). This is reflected in the gender division of labour in the seaweed value chain where women dominate the upstream activities (production of dried seaweed) and locally based downstream activities (processing seaweed into powder or value-added products). Of the people interviewed for this study, all processors were women, but all seaweed buyers, who tend to be in a better bargaining position and to earn more, were men.

Paying attention to gender-related differences highlights the fact that while women may dominate seaweed farming, they tend to be disadvantaged in their access to key resources. This reflects wider patterns in Tanzania, with women much less likely than men to receive cash earnings for the work they do (56% and 89%, respectively); among couples in which women earn cash, two-thirds of women say they earn less than their husbands (EDS-MIS, 2015, 2016: 325). More men own houses than women, and a slightly higher percentage of men own land (37% against 34% of women), but in Zanzibar, only 9% of women own land (ibid). Another major gender-related difference very relevant to seaweed farming is that women are less likely to know how to swim (Mulligan, 2016; Milele Zanzibar Foundation, 2021). While it is notable that this was not mentioned by farmers interviewed, swimming ability influences the farming activities they are able to undertake and therefore limits the location of their farm to shallow waters. Brugère, Msuya, Jiddawi, Nyonje, & Maly (2020), covering the Sea PoWer project conducted in Zanzibar that aimed to empower women seaweed farmers in tubular net technology/technique for seaweed production, noted that the major challenge/risk as perceived by the women was going to the open sea. The project aimed, among other things, to equip them with useful skills such as boat handling and swimming.

A gender lens also helps interrogate whether or not income from seaweed farming changes women's workload in productive and reproductive activities. Both men and women farmers engage in multiple income-generating activities, but women's roles are disproportionately associated with unpaid care work compared to men's roles, further limiting their access to equal opportunities (Songwe et al., 2016). In Songo Songo Island (Lindi), Besta (2013) explored how the income of female seaweed farmers affected gender relations in their households and whether their bargaining power changes as their income from seaweed farming declines. Among key findings were the fact that domestic tensions would arise over women's new earning opportunities from activities such as seaweed farming, especially if men's income was not increasing or was declining due to pressure on other marine resources. Women's increased work in farming seaweed left them with less time for household and childcare tasks, which were often resented by their husbands (Besta, ibid). A previous study in Zanzibar highlighted that most women work despite pregnancy or illness, which increases health risks, and suggests poor living standards and the risk of losing important income (Fröcklin et al., 2012). Both basic needs poverty and food poverty are more pronounced in female-headed households compared to their male counterparts (see Table 3).

Overall, the decline in seaweed production due to diseases and other environmental hazards has the potential to significantly affect farmers and their households, given that most fall within the lowest and second wealth quintile. This is particularly the case for farmers living in Lindi, Mtwara and, to a lesser degree, in Pemba. Women are likely to be the worst affected, especially in women-headed households, because of their disproportionate reproductive activities and lower access to training and other assets.

Capacities

The next step of the conceptual framework assesses the response of seaweed farmers within the context of the risk drivers analysed above. Sections below outline their strategies to deal with risks to seaweed production and which factors support or hinder the implementation of those strategies

Strategies to deal with risks to seaweed production

1. Farm maintenance

Farmers aim to control yield losses through farm maintenance, getting rid of pests and encroaching marine plants. They inspect the crops for disease, especially ice-ice, and manage the risk of pest infestation by weeding or harvesting when appropriate. Campbell et al. (2022) established the links between farmers' knowledge of biosecurity and their farming practices but showed that the links between their knowledge and their practices of cultivating seaweed in ways that reduce the exposure to biological hazards were generally poor. One of the main strategies farmers rely on to deal with challenges is increasing the amount of time spent on farm maintenance, but farming activities take place during the low tide in daylight, and the timing of low tide limits the time available for maintenance to one fortnight per month. Additionally, the off-bottom practice clearly limits farm maintenance in Tanzania compared to other countries like the Philippines, where a diverse range of cultivation techniques allows farmers to access their farm independently of the tides and conduct more frequent and regular maintenance (Mateo et al., 2021). Farmers interviewed in Tanzania did not spontaneously mention preventive actions such as disinfecting the ropes between cultivation cycles by sun-drying the equipment for 2–3 days (Mateo et al., ibid) though Rusekwa et al. (2020) reported that some Tanzanian seaweed farmers are implementing these simple measures, by drying ropes between harvests.

2. Wait-and-see approach

In Zanzibar, in both Unguja and Pemba sites, farmers affected by pests or disease will wait to gauge if the site will recover of its own accord, usually for a single growth cycle which lasts between 45 and 60 days. "When my seaweed is affected by diseases, I just leave it until it recovers itself" (Male farmer, 40 years, Kidoti, Unguja). This "wait-and-see" approach suggests that those who follow it can wait out a growth cycle either partly or in its entirety. This means that projected yields are lower and so are the returns to the farmer. Only those who can diversify their livelihoods (see below) or rely on the income of another member of their household can afford to wait and see. Farmers in Mtwara and Lindi, on the mainland, do not "wait and see", reflecting the fact that a higher proportion of them fall into the lower wealth quintiles, as shown in Table 3. In a few instances, farmers reported harvesting when the onset of disease is observed in a bid to reduce their loss: "I would harvest earlier and shift planting areas or wait for die off and replant" (Farmer, Woman, 47 years, Kidoti, Unguja). However, where it is used, the "wait-and-see" approach allows pests and diseases to spread, potentially carrying over to the next growth cycle – especially when farmers preserve (infected) cuttings for the next cycle of planting.

3. Relocation of the farm

Another major response to an outbreak of pests or disease is to relocate the farm within the immediate area. "I don't have many options; I move my farm to a less affected area and try again" (Woman farmer, 43 years, Chwaka, Unguja). Farmers in all four locations, both women and men, use this strategy which is aided by lack of restrictions with regard to accessing and using planting areas. However, farm relocation can introduce diseases to a new area particularly if the lines are relocated with the infested crop still attached rather than sourcing new, healthy seedlings or if the ropes are not disinfected (Mateo et al., 2021). Moreover, in all locations, the practice of relocation has led to suitable sea shores being overburdened with numerous farms, limiting the sustainability of this strategy. Seaweed farmers require marine space that is often coveted by the tourism and fisheries sectors along the shore (Masalu, 2000): "[. . .] fishers destroy our farms especially those who use trawl nets" (Farmer, woman, 48 years, Nalingu, Mtwara). "This time the seaweed has been spoiled a lot, we suspect it to be caused by explosion from fishers who use explosives for illegal fishing" (Farmer, man, 45 years, Chokocho, Pemba). Relocation could be an efficient strategy if the farm is relocated to deeper and cooler waters, but, as noted earlier, this option is not available to most farmers who cannot afford a boat and who lack swimming skills. Women in particular are therefore restricted to farming in the warmer shallow areas (Milele Zanzibar Foundation, 2021). Only farmers who are able to farm in deeper waters will be able to cope with the increased occurrence of diseases and the reduction of suitable space over time: Msuya (2020) and Shimba et al. (2021) have observed farmers, mostly men, recently relocating their farms to deep waters in Unguja and other sites.

4. Alternative seed sources and planting materials

The overuse of the same seed was stressed by some of the farmers, particularly in Unguja, as the leading cause of disease outbreaks and crop failure. "We are experiencing crop failure because we are using the same seeds that were imported many years ago and therefore have lost its quality" (Woman, Farmer, 50 years, Chwaka, Unguja).

To limit this, farmers in Mtwara, Unguja and Pemba often use seed supplied by neighbours through an informal, non-economic transaction: "[I] replant using seeds from my neighbour" (Woman farmer, 50 years, Chwaka, Unguja); "When seaweed is affected, I take seed from a neighbouring farm" (Woman farmer, 46 years, Makangale, Pemba). However, the quality of the seed is unknown, and the proximity of the neighbouring farm to the location of the infected farm does not alleviate the exposure of the lines to pests and disease. Ensuring access for farmers to healthy seeds from resistant varieties is one of the major recommendations cited in the literature (Cottier-Cook et al., 2016; Brakel et al., 2021; Hurtado, Neish, & Critchley, 2019). However, there is no seed bank in Tanzania or other facilities where farmers could source healthy seedlings.

5. Temporary suspension of farming activities

Key informant interviews noted that the overall number of seaweed farmers fluctuates: increasing in some areas and reducing in others. This is indicative of a third coping strategy where farmers suspend their farming activities for a time in light of the challenges they face. Interviewees related this primarily to price fluctuation: "Seaweed farmers are leaving seaweed farming due to two reasons; first the price of seaweed is small compared to the investments we are putting in it, and secondly seaweed is really affected by diseases nowadays" (Farmer, woman, 50 years, Chwaka, Unguja); "The number of farmers went down, but now it has started increase because the price of seaweed has gone up for the moment" (Collector, man, 45 years, Chwaka, Unguja);

> The number of seaweed farmers is growing up here at our village, because the profit of seaweed farming is increasing for example last year, we have been selling our dried seaweed for TSh 400 kg^{-1} but this year is TSh 600 kg^{-1} so many farmers are encouraged to come in and do seaweed farming. (Farmer, woman, 48 years, Nalingu, Mtwara)

Overall, interviewees agreed that the number of farmers is decreasing, disheartened by the low returns of seaweed farming compared to the investment they put in and by the outbreak of diseases. In Unguja, between the initial field visit in 2019 and a subsequent visit conducted in 2020, seaweed farming had been suspended, and the farms had been abandoned. Interviewees said they had temporarily stopped cultivating seaweed due to the loss of their crops.

6. Livelihood diversification

On average, respondents in Unguja and Pemba had worked in seaweed farming for between 15 and 20 years, respectively, against 4–6 years in Lindi and Mtwara. But the seaweed industry is a leading source of livelihoods across all four sites, and farmers' general opinion is that the income from seaweed has helped them cater for their needs. "The number of farmers is increasing as other businesses do not pay like seaweed" (Woman farmer, 46 years, Makangale, Pemba). However, in light of the challenges linked to disease outbreaks or price fluctuations, farmers do not rely solely on seaweed production. They engage in additional activities to secure other sources of income. Seaweed farmers from all four sites practice fishing (either themselves or someone from their household) to supplement their income. Men fishers tend to go out in boats, while women fishers will collect shellfish (cockles and oysters), octopus and lobsters along the intertidal zones where their farms are located. Most respondents also practice terrestrial agriculture, with respondents of both genders selling fruits, herbs and vegetable crops. Some operate small businesses, from managing produce stalls to restaurants and carpentry businesses. "I don't stop seaweed farming, instead I run a small business alongside it" (Woman farmer, 46 years, Makangale, Pemba). Some men reported seeking low-skilled employment such as security work. Of all four sites, Lindi had the fewest alternative sources of livelihood: one-quarter of informants depend solely on seaweed farming, while farmers in Unguja and Pemba rely on agriculture as a significant alternative livelihood. In Unguja, farmers reported gaining additional income from other household members practicing fishing or agriculture. Across all four sites, few seaweed farmers participate in the tourism industry because of their negative perceptions of the impacts of tourism on local values (Milele Zanzibar Foundation, 2021). Seaweed farmers tend to diversify their livelihoods within "traditional" sectors (Makame, 2013; Milele Zanzibar Foundation, 2021). However, their ability to rely on alternative livelihoods such as agriculture depends largely on climatic conditions which, like seaweed farming, are adversely impacted by extreme weather events that limit the benefits of livelihood diversification both in the short and the long term.

Factors supporting or hindering farmers' resilience capacities

There are few institutional and social barriers to engaging in seaweed farming, which adds to its attractiveness as a source of livelihoods. Given seaweed farmers' vulnerability to the risks outlined above, it is important to examine what is available to them to strengthen their resilience strategies.

1. Existence of support infrastructure

Seaweed farmers, particularly in Zanzibar, can benefit from government-run support systems including the Seaweed Cluster initiative, cooperatives, programmes set up by Non-Governmental Organizations (NGOs), the work of academics and research institutes or initiatives by the government. Cooperatives have helped farmers develop value addition activities and have shared knowledge on farming techniques and diseases. More cooperatives exist in Unguja and Pemba compared to Lindi and Mtwara, reflecting the different length of time seaweed has been produced in each of the four sites. Many have expanded to include small-scale processors as well as farmers: processors tend to operate communal farms in addition to their own individual farms to obtain the necessary quantity of supply. Women make up over 75% of cooperative membership. Farmers perceived that cooperative membership has advantages, as shown in Table 4. However, the predominant feeling among was that current support to cooperatives was inadequate and that most cooperatives were inactive or did not receive support: "I am not better supported even as part of a cooperative" (Coopperative member, Farmer, man, Songo Songo, Lindi). In one village in Unguja, the cooperative stopped due to the low returns from seaweed production. Farmers thought the government could better support cooperatives by controlling prices and providing inputs.

Other externally supported initiatives have focused on sharing knowledge and providing training to produce handcrafted products from seaweeds. However, local authority representatives are often not aware of policies pertaining to seaweed cultivation, leading to a significant gap in understanding of how to implement the biosecurity measures that are crucial for developing the sector (Rusekwa et al., 2020). Moreover, there are no policies encouraging research to develop resistant varieties and to create hatcheries able to distribute healthy seeds to farmers. Training regarding alternative cultivation techniques that will allow farmers to move away from the hot shallow waters has been ongoing since 2006 by ZaSCI and the Institute of Marine Sciences, but adoption is low because of women's inability to swim and lack of affordable boats (Msuya, 2017, 2020).

Finally, informants from seaweed exporting companies noted that while they offer loans to farmers, the repayment rates are low: "We used to provide loans to farmers, but no-repayment has made us stop" (Buyer, Fundo Island, Pemba). And some farmers either do not understand loan agreements or consider that they tie

Table 4. Perceived advantages of being a member of a cooperative.

Informants	Percentage (%) of farmers who are members	Perceived advantages as shared by respondents
Unguja	64.3	Easier to get loans, easier to attract sponsorship and support (incentives and planting materials) as a group
Pemba	35	Easier to obtain support as part of a cooperative
Lindi	66.7	Beneficial in obtaining governmental support and increased trustworthiness value
Mtwara	25	The government is more likely to provide financial support to a cooperative, and it is easier to get loans as part of a group, increased trustworthiness and improved access to training

them too much to one company: “We give the farmers the planting inputs with the agreement that they will sell the produce to us, however some farmers do not abide by this arrangement, selling to another company” (Buyer, Unguja).

2. Regulations and legislations

Ashford & Hall (2011) contend that sustainable development requires stimulation from regulation, with a well-regulated industry being more likely to attract financial institutions that can offer affordable support, help farmers start or continue following a shock and protect the industry in general. Seaweed farmers interviewed for this study observed that social support is only effective if seaweed cooperatives are backed up by strong institutional and financial governmental support. The Tanzanian government has measures in place to incentivize stakeholders in the seaweed value chain such as offering training and inputs and easing the costs associated with entry into markets by lowering tax on value-added products. However, there is no overarching legislation governing the seaweed industry. There is no national seaweed policy to regulate production and trade in seaweed or to support local authorities in designing or implementing regulations such as marine planning, trade practices, biosecurity measures or conservation of wild and farmed seaweed genetic resources (Rusekwa et al., 2020). For instance, farmers currently do not need a permit to set up their farm and do not need any certification stating that they are trained in farm management practices that could minimize the risk of disease outbreaks. And while there is a national ban on the use of mangrove forests (to make pegs for seaweed lines), there have been contradictory statements from politicians on villagers’ rights to use them, meaning that enforcing the ban has been difficult (Adams, 1992; Mshale, Senga, & Mwangi, 2017).

Farmers and local authorities noted that formalizing social networks, such as in the Zanzibar Seaweed Cluster and cooperatives, coupled with a functioning government support system would positively impact farmers’ resilience by contributing to knowledge sharing practices and investment options:

> Education is needed for farmers on how to cope with the risks and challenges; Farmers should be supported to get planting materials and other farming equipment at subsided/reduced price, also training on new planting technology as a coping strategy for climate change. Lastly the governments should be responsible for regulating the price not the buyers (Woman, Farmer, 40 years, Paje, Unguja).

Summary of resilience capacities

Table 5 categorizes the resilience capacities seaweed farmers employ. It shows that these are largely anticipative: farmers know the risks and implement actions in advance to minimize or reduce their impacts. For farmers who can rely on extra labour or who have time available, they will typically increase the amount of maintenance to look after their crops. Many choose to wait and see if their farm will recover from an outbreak, relocate their farms altogether and/or use alternative seeds so that they can try and create more suitable conditions for seaweed crops to grow.

While these anticipative capacities should help farmers harvest their produce and generate sufficient income to make a living, they are better seen as short-term coping mechanisms that do not help farmers in the long run. The wait-and-see approach allows diseases to spread around the infected farm; the relocation strategy can introduce diseases to a new area, and seeking alternative planting sources may not work if the underlying cause of disease is still present in the farming area and if the new seedlings are genetically similar (or identical) to those already used in the area.

The first four strategies could also be considered as absorptive because they help farmers absorb risks by containing the effects of diseases on seaweed production. But farmers are disadvantaged by their limited understanding of biosecurity and other cultivation techniques which could increase the options open to them for coping with environmental stresses. For example, there is no information about currents or nutrient flows and no training in different cultivation techniques such as hanging long-lines that would help them select and use improved production sites. Without this

Table 5. Categorization of the capacities employed by the farmers.

Farmers’ resilience capacities	Preventive	Anticipative	Absorptive	Adaptive	Transformative
1. Increased farm maintenance		✓	✓		
2. Wait-and-see approach		✓	✓		
3. Relocation of the farm for the next growth cycle		✓	✓		
4. Alternative source of seeds		✓	✓		
5. Diversification of livelihoods to complement income		✓	✓	✓	
6. Suspension of farming activities		✓			✓

knowledge, many Tanzanian farmers are stuck with the increasing disadvantage of using fixed off-bottom techniques in shallow waters (particularly women due to their lack of access to boats or swimming skills) which seriously limits their resilience to climate change. What this means is that although at first glance strategies such as farm relocation could appear to be adaptive, farmers' capacities are hindered by their limited understanding of biosecurity and their ability to implement alternative, biosecure options, making relocation a short-term strategy to absorb risks.

Livelihood diversification can be an anticipative, absorptive or adaptive capacity. It could be considered anticipative if farmers manage to plan which activities they (or someone from their household) can do in addition to farming seaweed to diversify their income, allowing them to mobilize the "wait-and-see" approach once a disease hits seaweed production. It could be considered an absorptive capacity – a more reactive coping mechanism – if farmers only find other sources of income after their farm has been affected by disease. And it could be considered as an adaptive capacity if it is part of a longer-term approach to generating a mix of income sources. Geographical location is an important factor in seaweed farmers' ability to diversify their livelihoods: whether their strategies are anticipative, absorptive or adaptive, their ability to find alternative sources of income will depend on their proximity to good agricultural land, to local markets or to the opportunities offered by the tourism industry.

The last strategy, the suspension of farming activities altogether, could also be seen as anticipative if the decision is made before investing too much time and resource into the seaweed growth cycle. It is linked to the "wait-and-see" approach if the decision to stop farming is temporary. However, when farmers permanently decide to stop farming and manage to secure alternative sources of income, this strategy is considered transformative as it radically changes the primary source of livelihoods – not necessarily in a positive manner.

Discussion

How these different capacities influence resilience outcomes is largely dependent on the timeframe being considered. As introduced in the first part of this paper, the Ecosystem Approach to Aquaculture encapsulates resilience as the ability to encounter and continue past the pressure and shocks affecting an aquaculture system by either resisting or adapting to changes (Brugère et al., 2018). This ability may be related to socio-economic resilience such as alternative employment opportunities and to ecological resilience such as the degree to which physical environments and ecosystem processes are able to adapt to changes including ocean warming and pollution.

Previous studies have highlighted how seaweed farming has improved the socio-economic conditions of coastal communities where other livelihood options are scarce (Eggertsen & Halling, 2020), particularly for women, many of whom have attained independence and financial security (Besta, 2013; Msuya, 2006). Although climate change and environmental degradation have increased the risks of seaweed production, with few sources of formal employment, many people in coastal communities in Tanzania have turned to seaweed farming for all or part of their livelihoods.

The set of anticipative, absorptive and adaptive capacities farmers mobilize allow many of them to continue cultivating seaweed and generating a large part of their household's income. The analysis presented here shows that as long as seaweed production provides them with part of their livelihood, the capacities they mobilize to maintain their farming activities contribute to their resilience. However, it does so only in the short term because of the various limitations outlined above, including the fact that cultivation techniques still rely on seeds that are not resistant to diseases or adapted to rising water temperatures and changes of salinity in shallow waters. None of the strategies farmers employ can address the underlying causes of disease outbreaks (Msuya, 2020) or the loss of vigour of cultivated varieties: these require large-scale interventions such as regulations to manage biosecurity risks and government-backed schemes to inform and train farmers in new cultivation techniques and provide them with new sources of seeds. Such interventions could help reduce seaweed farmers' exposure and vulnerability to environmental stress and maintain seaweed production in the long term.

Livelihood diversification is, at present, the only way for seaweed farmers to secure or increase their income. However, this adaptive strategy is not always sustainable. Some farmers may move into fishing, but this can be problematic where the area is saturated with fisherfolk who are already intensifying their fishing activities to cope with the ongoing decline of fish stocks (Suckall et al., 2014). Fishing may therefore provide short-term relief to seaweed farmers, but overfishing contributes to species decline which negatively affects long-run development goals. Moreover, seaweed farmers who turn to alternative livelihoods in aquaculture or agriculture continue to face risks from the adverse impacts of climate change. Suspending seaweed farming activities altogether might help farmers to become more resilient if their alternative source(s) of income provide them with better returns, better working conditions or new opportunities. However, such opportunities are few and far between in Tanzanian coastal communities. Men interviewed in this study generally reported engaging in a more diverse set of livelihoods than women, but overall, seaweed farming has tended to attract people from low-income backgrounds who are unable to find well-remunerated employment – typically women with childcare responsibilities. Suspending seaweed farming could be a positive adaptive strategy for the minority of farmers who can find a better job, but for most farmers, it is likely to be a last-resort strategy which leaves them with few or no alternatives and reduces their resilience outcomes.

To counteract these challenges, many farmers, particularly women, rely on social support systems such as cooperatives. These have supported the development of value addition activities and shared knowledge of farming techniques and disease management. Some cooperative members have been able to progress from seaweed production to small-scale processing and value addition. However, declining market prices, the lack of local processing opportunities and limited domestic markets mean that for most farmers seaweed production generates low profits. Most value addition occurs further up the value chain outside Tanzania (Eggertsen & Halling, 2020; Valderrama, Cai, Hishamunda, & Ridler, 2013). Seaweed farmers have few strategies to cope with the low prices: Valderrama et al. (2015) noted that scaling up farming operations could help ensure the sustainability of seaweed production though it is unclear what overall effect this would have on the livelihoods of those who currently rely on seaweed farming.

In summary, none of the observed capacities are transformative, i.e., they do not reflect farmer's strategies to transform their conditions and reduce their vulnerability to risks and climate change and ensure the sustainability of seaweed farming. As this is the first attempt to analyse seaweed farmers' resilience capacities according to the framework developed by Manyena et al. (2019), there are no directly comparable studies. However, our findings suggest that in Tanzania, individual farmers cannot possibly address some of the causes of their vulnerability such as declining market prices or the lack of local processing opportunities, themselves. Their transformative resilience should rather be assessed and supported at a community or society level.

Conclusion

Seaweed farmers in Tanzania mobilize resources within their means to increase their resilience in the face of climate change and environmental and biological hazards. However, some of their resilience strategies have shortcomings as they do not address the causes of the declining production of seaweed crops such as the increasing temperature of shallow water where seaweed is produced, the lack of healthy seeds and reliance on a limited variety of seaweeds. Nor can they take advantage of training that would help them develop to more efficient farming techniques in deeper waters. Overall, seaweed farmers' current capacities to cope with the decline in the seaweed production do not allow coastal communities in Tanzania to bounce forward to a more sustainable form of seaweed farming.

Seaweed farming faces several challenges to its sustainability. From an economic perspective, limited regulations may be attractive in terms of encouraging entry into the industry. However, a lack of secured support from government or the private sector creates a loophole that leaves farmers exposed to shocks, with no compensation for losses which would enable them to invest in alternative cultivation techniques. From a social perspective, knowledge sharing is currently largely informal (at farm gate) with limited formal training opportunities, limiting farmers' resilience and subsequent growth of the industry. From an environmental perspective, strategies such as relocating farms can reduce resilience in the long term as they can lead to the oversaturation of the space and overuse of other environmental resources such as the (slow growing) mangrove forest.

Seaweed farming initially showed great potential to improve livelihoods in coastal communities in Tanzania. While seaweed farmers have developed a range of strategies to improve their resilience, these on their own are not enough to cope with the effects of climate change and environmental degradation. Improving seaweed farmers' resilience in line with SDG 13 (Climate Action) and 14 (Life below Water) requires coordinated support and investment by the government, the seaweed industry and other partners such as research organizations to develop seed banks and improved varieties, increase farmers' awareness of improved technologies and work with women and men farmers to strengthen their absorptive and adaptive capacities.

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