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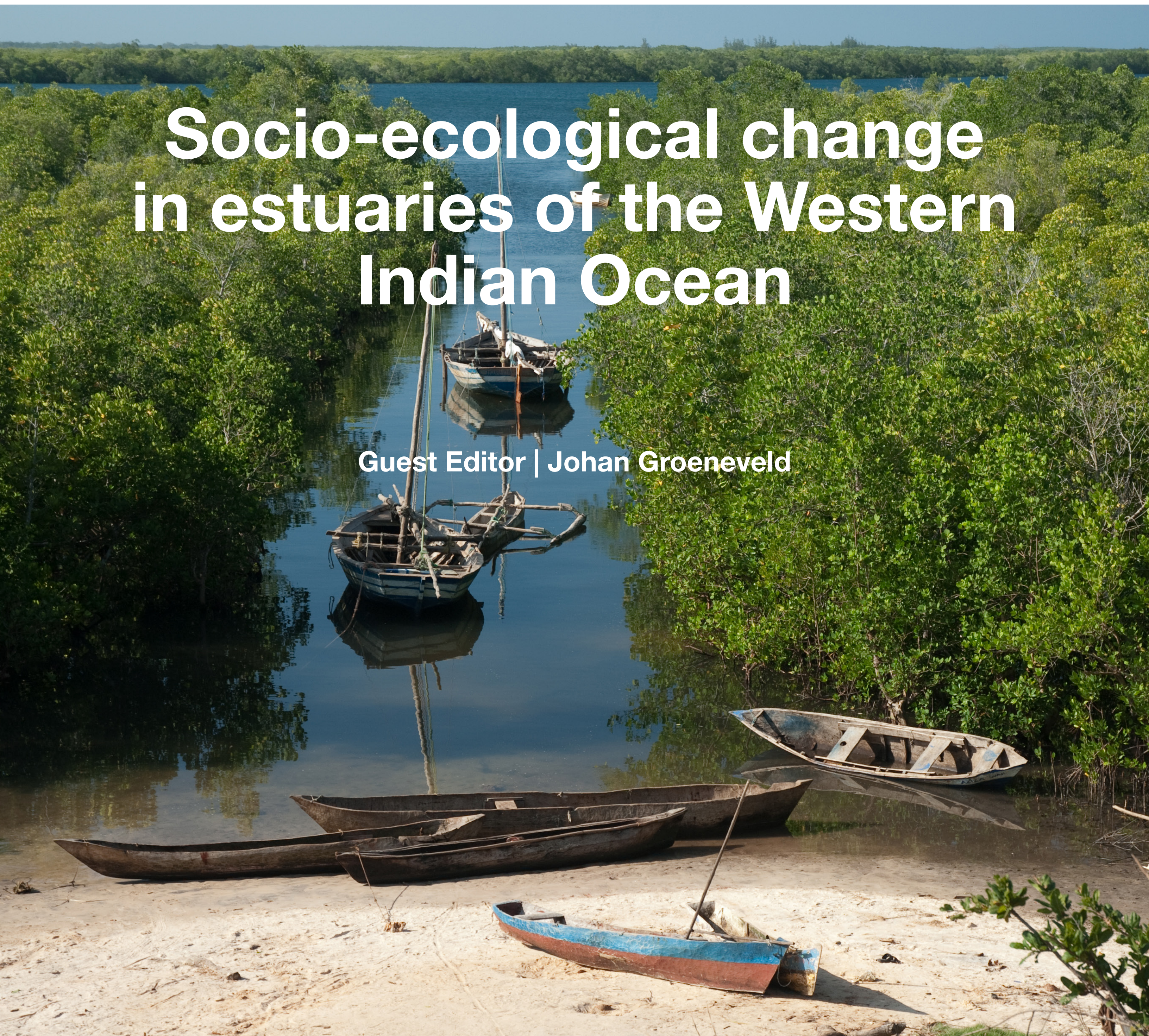

# Socio-ecological change in estuaries of the Western Indian Ocean

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Cover image: The Rovuma Estuary creeks near Quionga in Mozambique. © José Paula, 2007

# Natural resource-use in the Lower Tana River Delta based on household surveys and remote sensing of land cover and land use patterns

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## Abstract

Household survey data and spatially explicit Sentinel-2 satellite images of land cover and land use during the dry and wet seasons were used to investigate livelihood strategies in the Lower Tana River Delta in Kenya, where food security and economic activity rely almost exclusively on ecosystem goods and services. Land cover classification of satellite imagery successfully showed seasonal changes to estuary-related vegetation and habitats from which land use cycles could be inferred. Flood-recession agriculture and part-time fishing were the most common activities at Ozi village, some 10 km upstream from the estuary mouth, whereas full-time fishing dominated activities at Kipini town, where the Tana Estuary discharges into Ungwana Bay. Seasonality of fishing at Kipini depended on favourable sea conditions, arrival of migrant fishers and peaks in shrimp abundance. Seasonality of agriculture at Ozi depended on the freshwater flooding regime, visible in satellite images as an inverse relationship of areas covered by wetlands and cultivated lands. The predominance of fishing assets at Kipini indicated specialization, which underlies a socio-economic network of fish processing, marketing, distribution and logistical support services. In contrast, mixed farming assets and traditional fishing gear at Ozi reflected more diversified farmer-fisher livelihoods, as a risk avoidance strategy. Key outcomes of this study were that land cover and land use were strongly seasonal, that coastal and upstream communities in the Tana Estuary relied on different combinations of ecosystem goods and services, and that livelihood strategies at the two locations differed fundamentally. Combining social, spatial and ecological data to describe socio-ecological systems typical of the Tana Estuary provided a broad platform for shared resource management strategies.

**Keywords:** Tana Estuary, resource-use, livelihoods, artisanal fishing, flood-recession farming

## Introduction

Deltas and estuaries of the Western Indian Ocean (WIO) form unique and highly productive wetland ecosystems, including mosaics of mangrove and riverine forests, floodplain grasslands, vegetated sand dunes, brackish water habitats and seasonal freshwater lakes (Kitheka *et al*., 1998; Hamerlynck *et al*., 2010; Scheren *et al*., 2016). They are rich in natural resources and have high socio-economic importance as a source of food, freshwater, fuelwood and building materials to local communities. Rural livelihood strategies associated with these deltas are adapted to seasonal flooding patterns, and are diversified and often complementary (Duvail *et al*., 2017).

The Tana River Delta in Kenya discharges into Ungwana Bay through four main estuaries – the main channel that discharges into the bay at Kipini town

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(hereafter called Tana Estuary), Mto Kilifi, Mto Tana and Mto Moni (Scheren *et al*., 2016). The Tana Estuary is typical of the WIO region, where seasonal flooding replenishes freshwater resources, nutrients and sediments (Leauthaud *et al*., 2013; Duvail *et al*., 2017). Livelihood activities around the estuary are highly diverse, including typical 'fish-based farming systems' made up of mixed fishing/farming households (Hamerlynck *et al*., 2020). Livelihood activities are organized according to the availability of arable land, adequate fresh water supply, access rights, cultural institutions, and social and demographic dynamics (Smalley and Corbera, 2012). Key activities are flood-recession farming of rice, horticulture of mangoes, coconuts, bananas, beans and vegetables on sandy levees, and maize in mixed soils, fishing in freshwater wetlands, the estuary and nearshore Ungwana Bay, livestock herding on communal rangeland, and small-scale businesses to supply basic needs (Hamerlynck *et al*., 2010, 2020).

Small-scale fisheries are a key socio-economic component of estuary-dependent livelihoods in the WIO (Dzoga *et al*., 2020; Manyenze *et al*., 2021; Mugabe *et al*., 2021). In the Ungwana Bay region, Ochiewo *et al*., (2006) identified fisher age, size of fishing vessel and fishing duration as factors that influenced yields from fishing, and Dzoga *et al*., (2018) found fishing communities to be vulnerable to ecological change. Conflicts between fishing sectors reflected competition for fish resources (Munga *et al*., 2014a), exacerbated by a seasonal influx of coastal migrant fishers (Fulanda *et al*., 2009). Dzoga *et al*., (2020) and Manyenze *et al*., (2021) described the fishing gear and crafts used in the Tana Estuary, selectivity of gear, and the key species in landings. Apart from the latter studies, research on fisheries resources and fishers have focused mainly on coastal and offshore resources in Ungwana Bay (Fulanda, 2003; Fulanda *et al*., 2011; Munga *et al*., 2012, 2013, 2014a, 2014b, 2016), but the importance of fishing in livelihood strategies around the Tana Estuary has received scant attention.

Agriculture is of great importance to the Kenyan economy, and even more so in rural areas such as Tana River County, where some 86 % of the inhabitants have livelihoods based on farming (Muraguri and Gioto, 2013; van Beukering *et al*., 2015). Not surprisingly, most socio-economic studies in the region have focused on the broader Tana River Basin, to address impacts of damming, water abstraction (Maingi and Marsh, 2002; van Beukering *et al*., 2015) and agricultural intrusions into adjacent habitats on livelihoods (Terer *et al*., 2004; Mireri *et al*., 2008; Lebrun *et al*., 2010; Duvail *et al*., 2012, 2017; Leauthaud *et al*., 2013; Krijtenburg and Evers, 2014). Ecosystem assessments of the Tana River Basin found substantial degradation in the upper catchment, moderate degradation in the middle catchment, and low degradation levels in the lower basin, which includes the present study area (Kamau and Wasonga, 2015; van Beukering *et al*., 2015). Despite low ecological degradation levels in the Tana Estuary, upstream water abstraction and land cover change for agriculture and economic development disrupt the volumes and seasonal pulses of freshwater flooding, thus affecting traditional livelihood strategies based on crop farming, fishing and livestock herding (Hamerlynck *et al*., 2010; Kamau and Wasonga, 2015; Kitheka and Mavuti, 2016; Mwaguni *et al*., 2016; Odhiambo-Ochiewo *et al*., 2016).

A key environmental management objective in developing countries is to devise appropriate strategies for natural resource use, without disrupting livelihood and food security imperatives (Sulu *et al*., 2015). In the WIO, formal (top-down) resource management strategies cannot be successfully implemented without accounting for pre-existing traditional resource management systems, which arose from a historical trial and error process (McClanahan *et al*., 2009; Benkenstein, 2013). Socio-ecological systems (2-way feedback relationships that link human to natural systems in a dynamic equilibrium) are complex and adaptive, and facilitate resilience and sustainability (Berkes *et al*., 2003; Gallopín, 2006; Ostrom, 2009). A multi-user and multifunctional socio-ecological entity, adapted to local conditions in the Lower Tana, has for centuries supported local communities while also maintaining exceptional biodiversity value (Terer *et al*., 2004; Hamerlynck *et al*., 2010), demonstrating high resilience and flexibility. Nevertheless, livelihoods are now under threat from the combined effects of climate change, altered river flow and flooding regimes caused by building of dams and land use change in catchment areas, and increasing exploitation of local resources to support a growing population (Hamerlynck *et al*., 2010; Duvail *et al*., 2017).

The use of household survey data to obtain information on household budgets (income and expenditure), assets and livelihood activities is explored by Deaton (1997), with Blythe *et al*. (2014) and Blythe (2014) providing good examples of studies on WIO small-scale fisheries. Remote sensing is a useful tool for mapping coastal and marine habitats (van Sydow, 2002) and critical ecosystems (e.g. mangroves) particularly in inaccessible regions (Kirui *et al*., 2013; Furaca *et al*., 2021). Depending on the spatial and spectral resolution and the image analysis used, satellite images can provide a cost-effective means of mapping physiognomic vegetation features (e.g. Marzialeti *et al*., 2019), coastal wetlands (Mahdavi *et al*., 2017) and coastline morphology (Kumar *et al*., 2010), including shoreline changes resulting from sediment deposition or floods (Shaghude *et al*., 2003). Remote sensing also lends itself to estimating socio-economic and social anthropological effects and changes in coastal communities, i.e. the spatial and structural changes of agriculture over time (Pricope *et al*., 2019; Furaca *et al*., 2021). The aims of this study were to assess the livelihood strategies of communities residing around the Tana Estuary, and their reliance on seasonally variable ecosystem goods and services, based on data from household surveys and a spatial analysis of land cover images. A spatially explicit baseline map of land cover and key livelihood activities is provided for two rural communities; Kipini town at the mouth of the Tana Estuary, and Ozi village, some 10 km upstream.


**Figure 1.** Sentinel-2 satellite imagery used for land cover changes over the seasonal cycle of high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019) rainfall in the Tana Estuary and lower delta Area of Interest (AOI).

## Materials and methods

Existing information on the geographical setting, ecosystems and socio-ecological importance, and key drivers of socio-ecological change around the Tana Estuary have been summarized in the introductory paper of this Special Issue (Groeneveld *et al*., 2021). Briefly, the Tana Estuary (Fig. 1) receives runoff from a medium-sized basin comprising the Central Kenya Highlands, particularly the southern slopes of Mount Kenya and eastern slopes of the Aberdare mountain ranges (Maingi and Marsh, 2002). The basin is seasonally flushed during the transitions between the Northeast (NE) and Southeast (SE) monsoons, although downstream flow is partially regulated by dams and changes in land-use (Scheren *et al*., 2016). The communities surrounding the Tana Estuary and lower delta comprise Pokomo, Orma, Bajuni and other smaller ethnic groups (Government of Kenya, 2009). Traditionally, Pokomo are farmers and riverine fishers while Orma are pastoralists (Leauthaud *et al*., 2013). The Ozi and Kipini study sites are inhabited by distinct communities. Ozi is almost entirely inhabited by Pokomo, whereas Kipini is multi-ethnic with several groups represented, also from other parts of Kenya. Both Kipini and Ozi were categorized as low-density developments; these two areas are quite remote in a county with population density of 8 persons/km$^2$ (Government of Kenya, 2019).

### Study area

An area of interest (143.41 km$^2$) was selected around the Tana Estuary incorporating the estuarine-related and supporting habitats across several zones. The zones were based on a combination of *in situ* estuarine attributes (e.g. salinity), information from satellite images of land cover and land use and ascertained knowledge of livelihood activities of inhabitants. On the ground data collection was concentrated in only two of six zones; around Kipini town and Ozi village. Zone 1 around Kipini (45.49 km$^2$) comprised mainly densely and sparsely distributed mangroves, barren land, grasslands, coastal and mixed forests, estuarine open water and cultivated land. Zone 2 around Ozi (9.28 km$^2$) comprised cultivated land, mainly rice paddies mixed with banana and mango farming, some fallow land, vegetated wetlands and mixed forests. The zones were used to define resource use activities as they related to land cover and land use.

### Spatial data collection

Remotely sensed images of the Tana Estuary were used to establish seasonal land cover changes. Sentinel-2 images from the European Space Agency Copernicus Program, available since 2016, were used with two criteria: that images had at least 5-6 month intervals to represent rainfall seasonality, and that cloud cover was <20 % of the area of interest. A land cover classification scheme was adapted from the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). The classification scheme comprised of 7 high-level categories and 23 sub-categories relevant to estuarine systems (Table 1). An object-based imagery analysis approach was adopted using a support vector machine classifier on a GIS (ArcMap™ GIS) using the RGB and NIR bands (Red, Green, Blue and Near-Infrared). Classification of land cover categories was carried out using the maximum likelihood classification algorithm. Model training and validation was conducted using a combination of ground truth methods. Limited study area access and human capacity mostly obligated the use of high-resolution imagery for this analysis step. Of 314 ground truth points used, 15 were geolocated ground photos, 81 were obtained from Google Earth™ imagery and 218 from ESRI base map imagery (source DigitalGlobe, 0.5 m resolution). Accuracy assessments were conducted using the overall classification accuracy, being the percentage of correctly classified samples of an error matrix and the Kappa statistic providing a statistically valid assessment of the classification quality. A Kappa value > 0.5 was considered as satisfactory for modelling land use change (Pontius, 2000).

### Household surveys and collection of other socio-economic data

The study proposal was approved by the Ethics Review Committee of Pwani University (No. ERC/MSc/016/2018) accredited by the National Commission for Science, Technology and Innovation (NACOSTI) of Kenya. A systematic sampling design was used for household surveys, in which each i$^{th}$ house was selected after dividing the total number of households in each village by the required sample size to get approximately 12.3 % coverage. Sample size for each village adopted calculations by Dzoga *et al*., (2018) which were determined by the infinite Cochran (1977) formula. The survey targeted household heads, where a household was defined as all individuals housed and dependent on one head (Kronen *et al*., 2007, 2012). In cases where the selected house could not be sampled, the next house was chosen, with the assistance of the local Beach Management Unit (BMU) chairman. Semi-structured interviews using questionnaires were conducted in Swahili, and the expression of new ideas was encouraged. Information was captured on household location, gender and age of household head, household size, livelihood activities, education level, and monthly income with variables on assets used for fishing and farming. Categories for livelihood activities were derived from the number of activities in which a household was engaged. Following Béné (2009), fisher households were grouped into two categories according to the importance of fish as a source of income: full-time fishers not engaged in any other activity for income generation; and part-time fishers that derive their income from fishing but are also engaged in other activities (e.g. fishing, farming

**Table 1.** Land Cover/ Land Use classification system and definitions used for Tana Estuary study (adapted from Michigan Resource Information System, MIRIS National Oceanic and Atmospheric Administration, NOAA, 1976).

| | ID | Land cover category | Definition |
|---|---|---|---|
| Water | 1 | Coastal open water | All areas of open coastal water. |
| | 2 | Estuarine plume | Formation of water resulting from the discharge of low-salinity water into marine waters of the ocean, forming a distinct layer of water on top of the seawater due to its lower density. |
| | 3 | Estuarine water | Partially enclosed water body where saltwater is measurably diluted with fresh water. |
| | 4 | Turbid estuarine water | Suspended sediment, muddy water within the estuary. Influenced by the catchment, runoff and/or recent rains/floods. |
| Developed Land | 5 | Medium density - formal development | Contains a mixture of residential, commercial and industrial development, including infrastructure. |
| | 6 | Low density - informal development | Sparsely distributed informal rural settlements. |
| Barren Land | 7 | Coastal bare unconsolidated sediment | Includes material such as sand that lacks vegetation and falls outside the intertidal zone along the coast. |
| | 8 | Coastal intertidal unconsolidated sediment | Includes material such as sand that is subject to inundation and redistribution due to the action of water. Substrates lack vegetation and falls within the intertidal zone. |
| | 9 | Estuarine intertidal unconsolidated sediment | Includes material such as sand within the estuary that is subject to inundation and redistribution due to the action of water. Substrates lack vegetation and falls within the intertidal zone. |
| Forest Land | 10 | Coastal forests | Woody vegetation closely located to the seashore. |
| | 11 | Disturbed forests | Areas dominated by woody vegetation in between agricultural land and developed areas. |
| | 12 | Mixed forests | Consists of forested areas where there is a mixture of woody vegetation and shrubland. |
| Grassland | 13 | Disturbed herbaceous | Areas dominated by grammanoid or herbaceous vegetation often occuring in between agricultural land and developed areas. Could include previous agricultural/transformed land now occupied by vegetation. |
| Cultivated Land | 14 | Subsistence - harvested land | Contains subsistence agricultural areas that are managed for the production of harvested row or field crops. Often fairly mixed in between fallow land. |
| | 15 | Subsistence - fallow land | Contains agricultural areas that have no physical indication of present agricultural use. These areas include both abandoned cropland and fields left fallow or in a process of a crop rotation cycle. An indication of inactive cropland is the presence of any woody stems in the field. |
| | 16 | Mariculture | Structures related to mariculture |

| | ID | Land cover category | Definition |
|---|---|---|---|
| Wetlands | 17 | Mangroves - densely distributed | Woody vegetated wetland areas and floodplain forests dominated by densely distributed mangroves. This could either be different mangrove species or well-established mangroves which appears to be densely packed. |
| | 18 | Mangroves - sparsely distributed | Forested wetland areas and floodplain forests dominated by sparsely distributed mangroves. This could either be different mangrove species or younger mangroves which appear to be more scattered. |
| | 19 | Swamp forests | Areas dominated by woody vegetation (other than mangroves) where the soil or substrate is periodically saturated with or covered with water. |
| | 20 | Intertidal mudflats | Areas of non-vegetated, natural cover that are subject to seasonal and tidal ponding, soil saturation, or flooding. |
| | 21 | Vegetated wetlands | Wetland areas dominated by lowland brush, shrubs and herbaceous vegetation. |
| | 22 | Non-vegetated wetlands | Wetland areas lacking vegetation. |
| | 23 | Vegetated wetlands burnt | Wetland areas that have burnt |

and others). Four categories were selected for education level; *viz* no education, primary education, secondary education and higher education. Focus group discussions were undertaken at the two study sites to define resource use activities in each estuary zone, based on the perceptions of locals.

Data on the numbers of fishing craft and gear types used by communities at Kipini and Ozi were obtained from Manyenze *et al*., (2021). Information on population demographics was obtained from reviewing existing data from the Kenya National Bureau of Statistics (Government of Kenya, 2009), and information on migrant fishers, vessel owners and crew as summarized by Fulanda *et al*., (2009).

## Results

### Land cover and estuary-related habitats

The first monsoon period (June, July) was considered to be 'high rainfall' and the hot, dry period after the second rains (February, March) to be the 'low rainfall' period for land cover comparisons. In this context, the lower delta is a highly dynamic system with changes dictated by annual flooding events. Satellite imagery showed a vastly different estuary during the high- (25.06.2017, 10.07.2018) compared to the low rainfall period (25.02.2018, 02.03.2019) (Fig. 1). Land cover classification using seasonal timestamps was successful in showing changes to estuary-related vegetation and habitats (Fig. 2). The sediment-laden water plume into Ungwana Bay with a dominant oligohaline salinity signature was associated with the high rainfall period. In contrast, the plume disappeared during dry periods, suggesting a stratified salinity gradient between upper and lower water masses.

For the accuracy assessment (i.e., how good the images and classifications were at depicting land cover), the 25.02.2018 image was used as it had the least amount and spread of clouds. Of 314 ground truth points, 12 were cloud-covered and had to be removed. An overall accuracy of 71 % was achieved (kappa value of 0.64) translating to a moderate to substantial strength of agreement. Classification classes contributing to lower accuracy scores were cultivated land (32 % modelled correctly), forests (28 % of modelled forests were actual forests after validation) and mudflats (50 % accurately classified after validation).

Across successive wet and dry cycles, the most prominent seasonal changes were observed in wetland, mangrove, cultivated land and grassland categories.

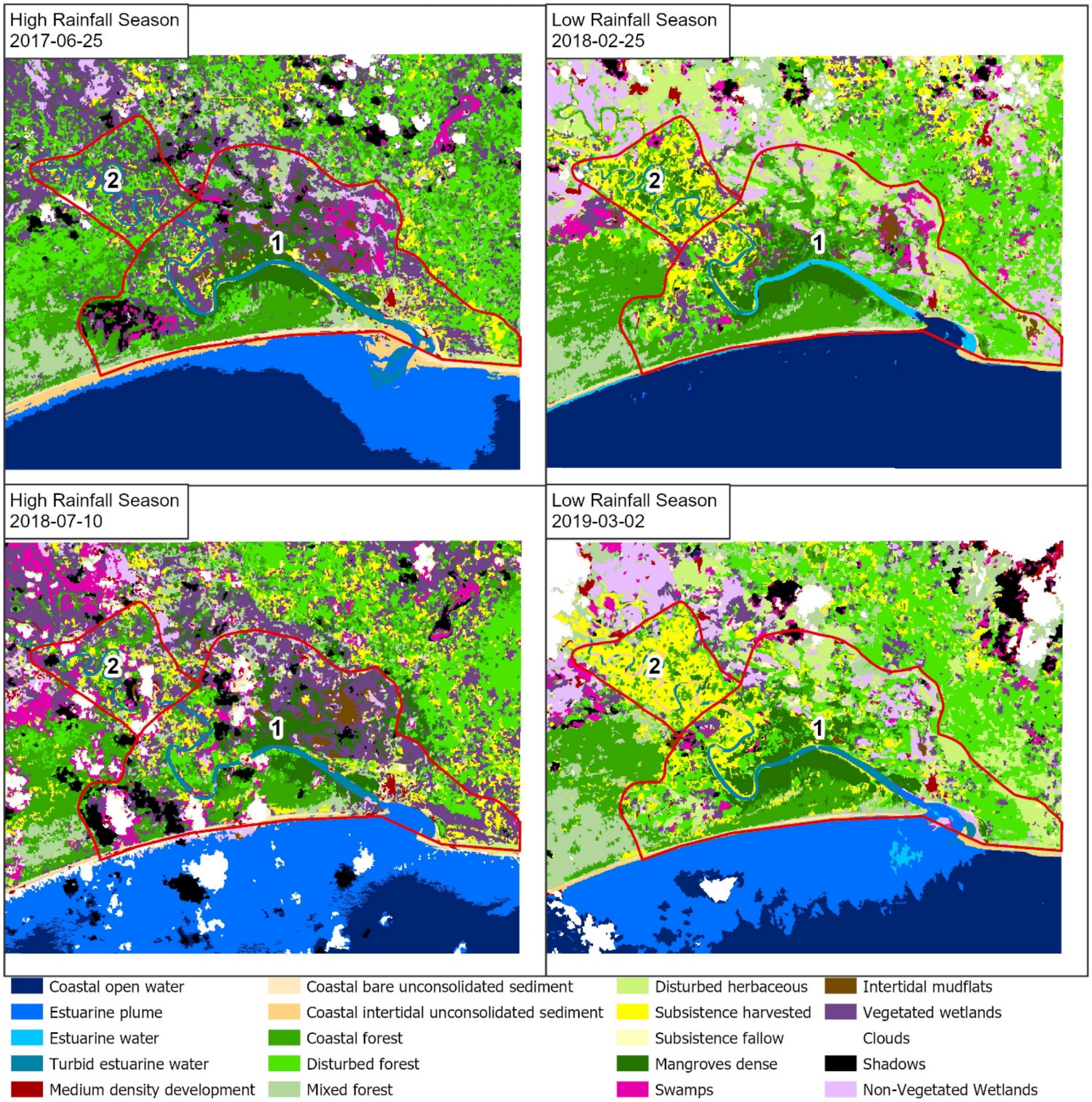


**Figure 2.** Land cover classification zones at Kipini (Zone 1) and Ozi (Zone 2) over the seasonal cycle of high and low rainfall in the Tana Estuary and lower delta.

Wetlands dominated during the wet seasons and were related to an increase in mangroves and a decrease in cultivated lands and grasslands, which increased during the dry season (Fig. 3). These changes had a marked influence on the temporal use of livelihood resources by inhabitants. In Zone 1 (influenced by Kipini), wetlands and grasslands decreased during the dry months, with cultivation increasing marginally across seasons after the high rainfall season (Fig. 4). Kipini residents were more reliant on fishing during the dry season, when prawns were seasonally abundant (Munga *et al.*, 2013), and depressions along the main channel in Zone 1 were flooded by marine waters during high tides, making flood plains unsuitable for crops such as rice. Grasslands in slightly elevated areas in Zone 1 increased when freshwater wetlands, further from the main channel, dried during the dry season, making Zone 1 suitable for cattle herding. Wetlands showed a strong seasonal rhythm, approximately doubling in size during the wet months. In Zone 2 (Ozi) the size of the wetlands and cultivated lands were inversely related, reflecting the expansion of rice paddies during

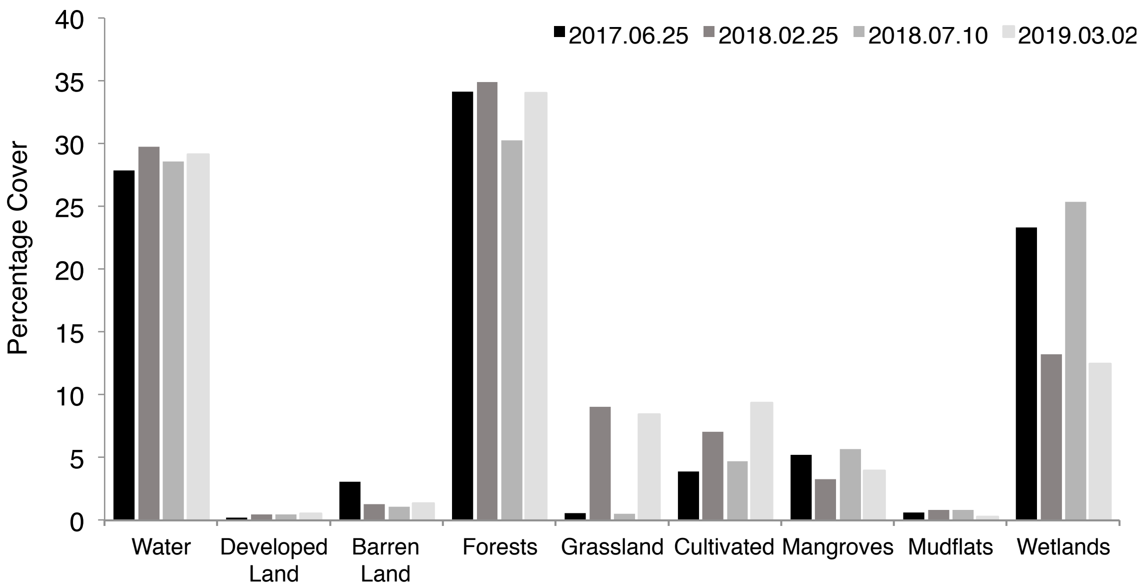


**Figure 3.** Tana Estuary and lower delta AOI seasonal land cover (%) change across estuarine function and habitat categories. Rainfall seasons are high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019).

the flood recession after the rainy season, as arable land becomes available for planting after floods (Fig. 4).

### Socio-economic analysis (demography, income and assets)

The population census (Government of Kenya, 2009) indicated a total of 801 and 389 households at Kipini town and Ozi village, respectively. Data from 146 households were analyzed comprising 71 from Kipini (8.9 % of households) and 75 from Ozi (19.3 % of households). Crop farming, fishing, livestock keeping, and other small businesses were key parts of local economies at the two sites. Farming was the main livelihood activity at Ozi compared to full-time fishing at Kipini (Fig. 5). By gender, farming was the preferred activity of men and women respondents (Fig. 5), but only men were full-time fishers. Some women fished part-time from the shore. Some 60 % of farmers had a secondary

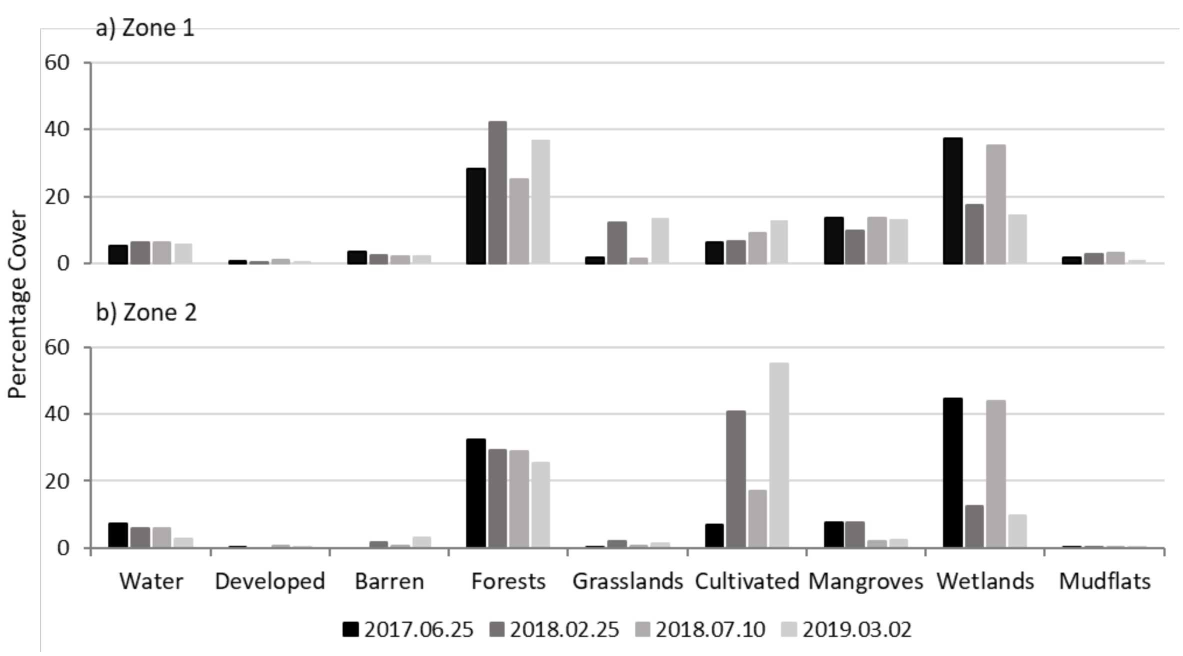


**Figure 4.** Tana Estuary and lower delta seasonal land-cover (%) change across categories associated with estuarine function and habitat in a) AOI Zone 1 (Kipini) and in b) Zone 2 (Ozi). Rainfall seasons are high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019).

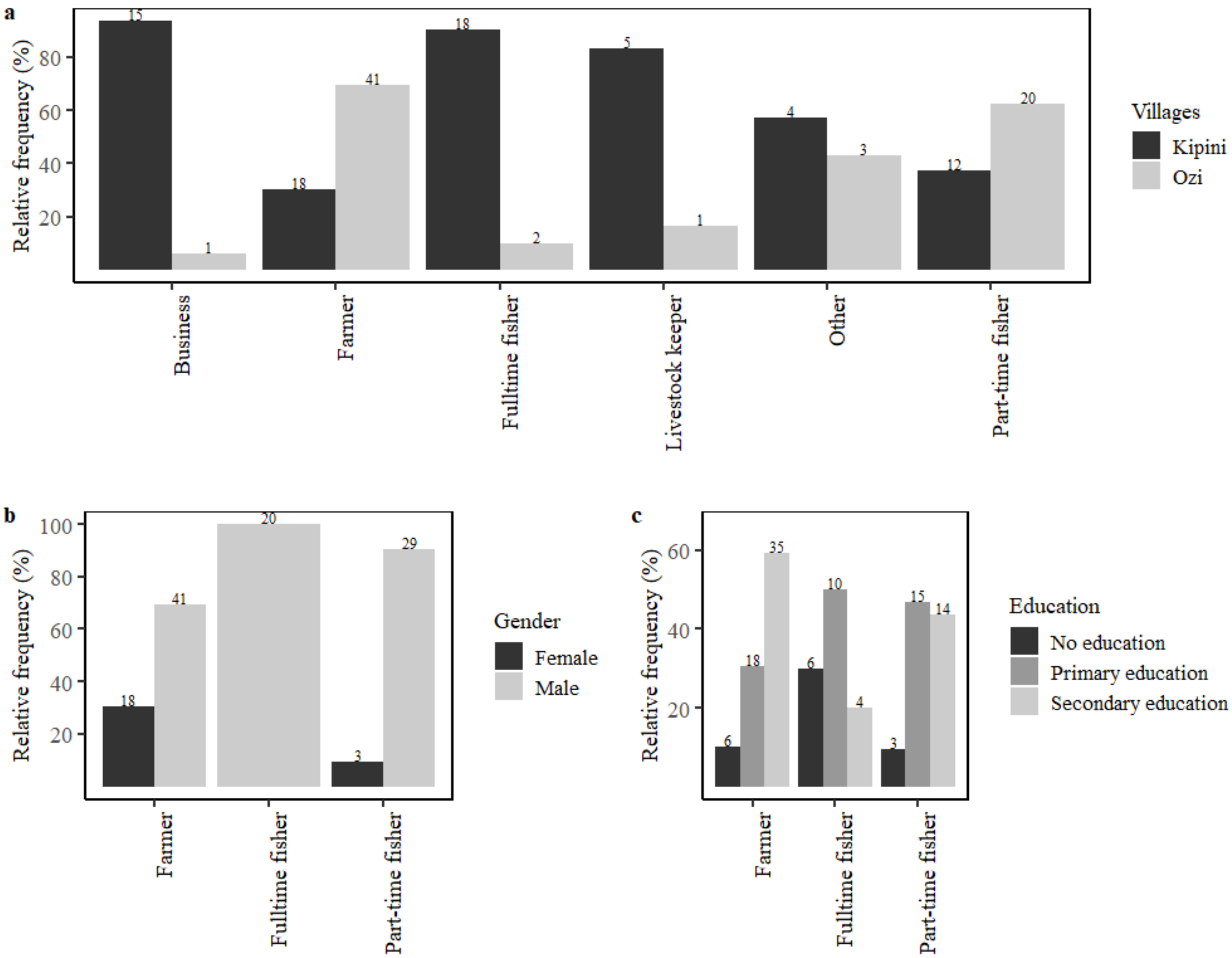


**Figure 5.** Relative frequency of livelihood activities in the Tana Estuary and lower delta, obtained from household survey data. The frequency of activities was compared: (a) by location; (b) by gender; and (c) by level of education.

**Table 2.** Relative importance of fishing crafts and fishing gear types at Kipini and Ozi, respectively, obtained from a shore-based survey of small-scale fisheries (see Manyenze *et al.* 2021; dash means not recorded).

| | Kipini | | Ozi | |
|---|---|---|---|---|
| **Fishing craft** | (n) | (prop) | (n) | (prop) |
| Canoes | 289 | 0.92 | 226 | 1.00 |
| Dhows | 22 | 0.07 | | |
| Fibreglass boat with outboard engine | 2 | 0.01 | | |
| **Fishing gear** | (n) | (prop) | (n) | (prop) |
| Gillnets | 242 | 0.62 | 32 | 0.14 |
| Seine nets | 73 | 0.19 | 40 | 0.17 |
| Hook-and-line | 73 | 0.19 | 16 | 0.07 |
| Traditional traps | - | - | 132 | 0.57 |
| Other | 5 | 0.01 | 13 | 0.06 |

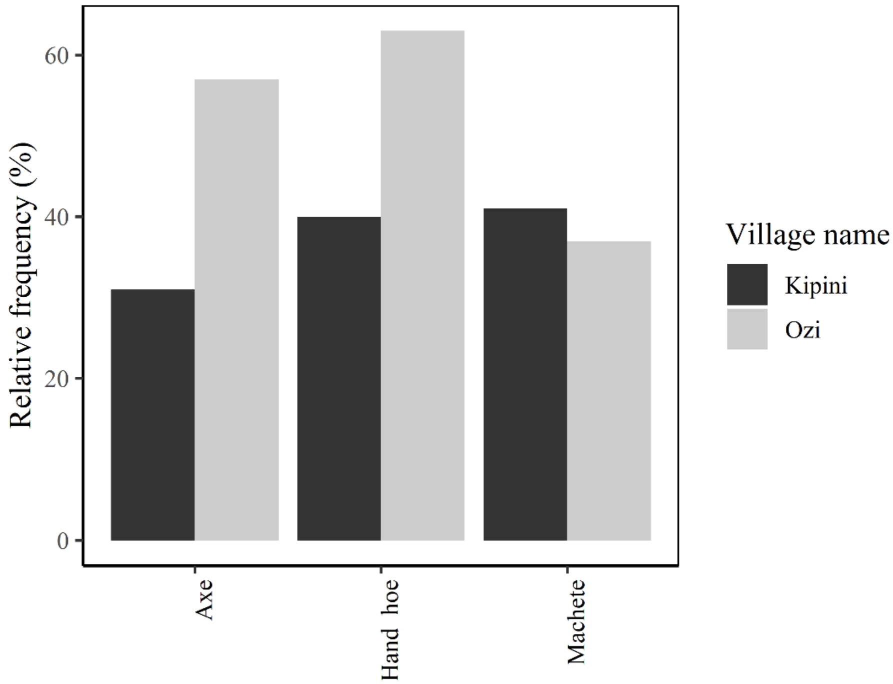


**Figure 6.** Relative number of farming assets and their distribution among communities at Kipini and Ozi.

school education, followed by 45 % of part-time fishers. Most full-time fishers had either a primary school education (~50 %) or had not been to school (~30 %). Household size of full-time fishers was 7 ± 3 people, and slightly fewer at 6 ± 3 for part-time fishers and farmers, respectively. Farmer household heads were 44 ± 14 yrs old, compared to part-time fisher household heads (42 ± 10 yrs) and full-time fishers (40 ± 8 yrs). A Kruskal-Wallis test indicated no significant difference in household size ($K = 1.4377$; $p = 0.4873$) and household head age ($K = 1.3493$; $p = 0.5093$) between the different livelihood activities.

Farmers earned an income of US$ 110 ± 70 per month, compared to US$ 140 ± 90 for full-time fishers. Combining the two activities as part-time fishers increased earnings to US$ 170 ± 100 per month. Men earned some 50 % more than women (US$ 150 ± 110 versus US$ 100 ± 80 per month). A Kruskal-Wallis test confirmed that the mean income of household heads differed significantly between livelihood activities ($K = 9.3147$; $p = 0.009$), and a pair-wise post-hoc comparison confirmed that farmer and part-time fisher incomes differed significantly ($p = 0.007$).

Dug-out canoes were the most common craft type at Kipini and Ozi, used for fishing and transporting people and goods (Table 2). Dhows and fiberglass boats with outboard engines were present at Kipini for use in Ungwana Bay, but they were absent from Ozi. Traditional traps made from locally available wood and fibre made up 57 % of gear used around Ozi, but they were absent from the Kipini landing site. The bulk of fishing gear at Kipini comprised of gillnets (62 %), seine nets (19 %) and hook-and-line (19 %, including longlines and handlines). Overall, assets used for fishing activities were more abundant at Kipini (62 % of all gears) than at Ozi. A greater proportion of respondents at Ozi owned farming tools than at Kipini, including axes (61 % of respondents at Ozi *versus* 39 % at Kipini) and hand hoes (65 % *versus* 35 %), but machetes were evenly distributed (47 % *versus* 53 %) (Fig. 6).

## Discussion

Household survey information confirmed that livelihood strategies at Kipini and Ozi differed according to the available natural resources, inferred from the land cover assessment. Farming (mainly flood recession agriculture) and fishing were the two most important economic elements, with their intensity varying spatially and seasonally. Full-time fishing as a livelihood source dominated at Kipini, where fishing in Ungwana Bay and the lower Tana Estuary provided employment opportunities to fishers, processors, distributors and in the maintenance of gear and craft. In contrast, flood recession agriculture dominated at Ozi, complemented by part-time fishing in the upper Tana Estuary.

Wetlands at Ozi approximately doubled during wet months, and cultivated land and wetlands were inversely related in this area (see Fig. 4). Rice is planted biannually at the start of each rainy season in paddies on the upper floodplains near Ozi. Paddies are located so that they are irrigated when daily incoming tides elevate fresh surface waters onto the floodplains (Terer *et al.*, 2004). Hedges between rice paddies (elevated by ~1 m) were often stabilized by banana plantations. Other crops such as maize, beans, squash, sweet potatoes and cassava are cultivated shortly after the floods on slightly higher and sandier zones. Leathaud *et al.* (2013) noted that crops were selected according to water requirements and planted along the hydrological upper floodplain-lower floodplain gradient, gradually following the recession after floods. Cultivated mango plantations were located further from the floodplain, on higher ground, although some large trees grew close to the riverbank near Ozi.

Part-time fishing at Ozi complemented the income from agriculture and increased seasonally during periods when fields are inundated by flood waters. Locally made traditional fish traps (mgono) are set as stationary gear in flooded areas and deeper water along the riverbank (Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). Trapping is a passive fishing method, and hence a farmer can leave the trap to fish while his effort is directed elsewhere. For example, traps and longlines (also a passive gear) can be set while in transit between crop fields, by foot or canoe, and retrieved on return. Apart from traps and longlines, sharpened sticks, seine nets and sometimes gillnets are also used for fishing in the mid and upper Tana Estuary (Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). Farming combined with part-time fishing contributed more to household incomes at Ozi than farming alone.

Full-time fishing at Kipini utilized both the bay and lower estuary, with access to extensive fishing grounds that include several productive habitat types and many different fish and invertebrate species. Household data indicated that fishing in Kipini is seasonal, with rough seas during the windy SE monsoon season restricting fishers to shallow waters and sheltered river channels. The SE monsoon coincides with a period of high rainfall and high shrimp abundance in the estuary and on mudbanks in Ungwana Bay (Munga *et al.*, 2013). During this period, monofilament nets attached to two mangrove poles are dragged over the substrate in shallow waters to catch shrimps. Shrimps fetch good prices in urban centers such as Mombasa and Malindi (Munga *et al.*, 2013) and are therefore popular target species. Migrant fishers arrive after the SE monsoon during calmer sea conditions to target finfish in productive areas in nearshore waters where the Tana Estuary discharges into Ungwana Bay (Fulanda *et al.*, 2011). The satellite images could not provide any additional information on the full-time fishery at Kipini.

Based on household information, livestock keeping was a household amenity rather than a livelihood source at the two study sites. Livestock roamed freely and were observed to drink from the estuary at Kipini, most likely during an ebb tide when freshwater at the surface replaced denser saline water. Terer *et al.* (2004) noted that livestock keeping was an important livelihood activity for pastoralists living further upstream from the present study sites, because of access to freshwater and grasslands on floodplains. The satellite images confirmed the seasonal expansion and contraction of grasslands. Pastoralists move livestock herds closer to the delta for grazing during the dry season, when riparian grasslands expand following the flood recession (Duvail *et al.*, 2017; Hamerlynck *et al.*, 2020).

The ownership of fishing and farming assets in the Ozi and Kipini communities reflected the dominant livelihood activities. At Ozi, dugout canoes were used for transport and fishing, but at Kipini the use of dugout canoes was augmented by larger seagoing vessels such as dhows. A broad range of gear types was used for fishing at both sites, but home-made traditional traps were the gear of choice at Ozi, compared to gillnets, seine nets and hook-and-line at Kipini (also see Munga *et al.*, 2014b; Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). A higher investment in fishing gear at Kipini reflected specialization in fishing as an economic activity to supply local markets. Kipini fishers spent more days per week fishing compared to Ozi, where flexible farmer-fisher livelihoods prevailed as a risk-avoidance strategy (Terer *et al.*, 2004; Duvail *et al.*, 2017; Hamerlynck *et al.*, 2010, 2020). Blythe *et al.* (2014) showed that specialized fishers in Mozambique adapted to declining catches by intensifying their fishing effort, in contrast to other groups without access to fishing gear, who adapted through diversification. They concluded that adaptation is a heterogeneous process that is influenced by multiple factors. Likewise, the results of the present study suggest that specialized fishers and farmer-fisher communities at the Tana Estuary would rely on different strategies to adapt to increased livelihood stressors, such as declining catch rates, droughts and floods.

Household surveys at Kipini and Ozi could not detect a difference in household size, or the age of household head, irrespective of livelihood strategies followed. Primary and secondary school education levels were most common, with fewer full-time fishers having a secondary education, presumably because migrant fishers without formal education were included in sampling. Mwangudza *et al*. (2016) similarly reported low education levels in resource dependent communities, which prevented them from acquiring the necessary skills to secure formal employment. Kipini recorded a higher number of respondents engaged in 'other businesses' (i.e. not fishing or farming) showing diversification, but Ozi remains a remote community, reliant on the exploitation of natural resources within an established socio-ecological entity. The low levels of formal education at both localities are expected to hinder adaptation to a modernizing economy (Benkenstein *et al*., 2013; Blythe *et al*., 2014).

The present study found important linkages between local livelihood strategies and natural resource distribution around the Tana Estuary. Critical questions that now need to be asked are how the two communities will adapt to the effects of climate change, population growth and the livelihood stressors brought by a modernizing economy and infrastructure development in catchment areas? Further semi-quantitative modelling of the socio-ecological entities described in the present study, to predict the effects of changes brought by governance initiatives, societal flux or natural perturbations, is provided by Santos *et al*., (2021).

In conclusion, complementary use of household survey data and satellite images to assess the relationship between livelihood strategies and seasonal flux in land cover and land use practices at the Tana Estuary provided several important insights. Full-time fishing dominated activities at Kipini, compared to farming (mainly flood-recession agriculture) and part-time fishing at Ozi. Activities at both locations were strongly seasonal, but not in synchrony. At Kipini, seasonality of fishing was determined by sea conditions in Ungwana Bay (unfavourable during the SE monsoon), arrival of migrant fishers and seasonal shrimp abundance in nearshore waters. At Ozi, the flooding regime determined seasonal agricultural and fishing activities, confirmed by the inverse relationship between wetlands and cultivated lands, and wetlands and grasslands, shown on satellite images. As a larger town with an established economy, Kipini offers diverse employment opportunities. In contrast, livelihood strategies at Ozi depended almost entirely on natural resource use, with flexibility to cope with variable resource availability. Key outcomes of this study were that land cover and land use were strongly seasonal, that coastal and upstream communities in the Tana Estuary relied on different combinations of ecosystem goods and services, and that fundamentally different livelihood strategies included both specialization and diversification. Environmental change will therefore affect the communities at Kipini and Ozi in different ways.

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## References

Benkenstein A (2013) Small-scale fisheries in a modernizing economy: Opportunities and challenges in Mozambique. Governance of Africa's Resources Programme, South African Institute of International Affairs Research Report 13. 53 pp

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

Berkes F, Colding J, Folke C (2003) Navigating social–ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK. 419 pp

Blythe JL, Murray G, Flaherty M (2014) Strengthening threatened communities through adaptation: insights from coastal Mozambique. Ecology and Society 19 (2): 1- 9

Blythe JL (2014) Resilience and social thresholds in small-scale fishing communities. Sustainability Science 10 (1): 157-165

Cochran WG (1977) Cochran-sampling Technique, third ed. John Wiley and Sons, New York. 448 pp

Deaton A (1997) The analysis of household surveys: a microeconometric approach to development policy. The World Bank. 490 pp [doi.org/10.1596/0-8018-5254-4]

Duvail S, Médard C, Hamerlynck O, Nyingi DW (2012) Land and water grabbing in an East African coastal wetland: The case of the Tana delta. Water Alternatives 5 (2): 322-343

Duvail S, Hamerlynck O, Paron P, Hervé D, Nyingi WD, Leone M (2017) The changing hydro-ecological dynamics of rivers and deltas of the Western Indian Ocean: Anthropogenic and environmental drivers, local adaptation and policy response. Comptes Rendus Geoscience 349 (6-7): 269-279

Dzoga M, Simatele D, Munga CN (2018) Assessment of ecological vulnerability to climate variability on coastal fishing communities: A study of Ungwana Bay and Lower Tana Estuary, Kenya. Ocean and Coastal Management 163:437-444

Dzoga M, Simatele D, Munga C (2020) Characterisation of artisanal catches in selected fishing areas of the Lower Tana Delta and Malindi-Ungwana Bay, Kenya. Western Indian Ocean Journal of Marine Science 19 (1): 45-53

Fulanda B (2003) Shrimp trawling in Ungwana Bay A threat to fishery resources. In: Hoorweg J, Muthiga N (eds) Recent advances in coastal ecology. African Studies Centre, Leiden. pp 233-243

Fulanda B, Munga CN, Ohtomi J, Osore M, Mugo R, Hossain MY (2009) The structure and evolution of the coastal migrant fishery of Kenya. Ocean and Coastal Management 52 (9): 459-466

Fulanda B, Ohtomi J, Mueni E, Kimani E (2011) Fishery trends, resource-use and management system in the Ungwana Bay fishery Kenya. Ocean and Coastal Management 54 (5): 401-414

Furaca NB, Hoguane AM, Mackay CF, Willemse M, Langa A (2021) Exploring urbanization and critical habitat loss through land cover change around the Bons Sinais Estuary, Mozambique. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 43-58

Gallopín GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change 16 (3): 293-303

Government of Kenya (2009) The 2009 Kenya population and housing census (Vol. 1). Kenya National Bureau of Statistics, Nairobi. 218 pp

Government of Kenya (2019) Kenya population and housing census (Vol. I: Population by County and Sub-County), Nairobi. 49 pp

Groeneveld J, Hoguane A, Kuguru B, Mackay CF, Munga C, Santos J (2021) Estuarize-WIO: A socio-ecological assessment of small-scale fisheries in estuaries of the Western Indian Ocean. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 1-15

Hamerlynck O, Nyunja J, Luke Q, Nyingi D, Lebrun D, Duvail S (2010) The communal forest, wetland, rangeland and agricultural landscape mosaics of the Lower Tana, Kenya: A socio-ecological entity in peril. Sustainable use of biological diversity in socio-ecological production landscapes. pp 54-184

Hamerlynck O, Nyingi DW, Paul JL and Duvail S (2020) Fish-based farming systems: maintaining ecosystem health and flexible livelihood portfolios. In: Dixon DP, Garrity JM, Boffa TO, Williams T, Amede C, Auricht R (eds) Farming systems and food security in Africa: Priorities for science and policy under global change. Earthsan food and agriculture. Routledge, Taylor & Francis Group. 638 pp

Kamau P, Wasonga U (2015) Ecosystem assessment of the Tana River Basin. In: van Beukering P, de Moel H (eds) The economics of ecosystem services of the Tana River Basin: Assessment of the impact of large infrastructural interventions. Institute for Environmental Studies, Amsterdam, Netherlands. 163 pp

Kirui KB, Kairo JG, Bosire J, Viergever KM, Rudra S, Huxham M, Briers RA (2013) Mapping of mangrove forest land cover change along the Kenya coastline using Landsat imagery. Ocean & Coastal Management 83: 19-24

Kitheka J, Ong'anda H, Nguli MM, Wakwabi E, Munga D, Kairu KK, Ntiba MJ (1998) Eastern Africa atlas of coastal resources: Kenya. United Nations Environment Programme, Nairobi. 114 pp

Kitheka JU, Mavuti KM (2016) Tana Delta and Sabaki Estuaries of Kenya: freshwater and sediment input, upstream threats and management challenges. In: Diop S, Scheren P, Machiwa JF (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 329 pp

Krijtenburg F, Evers SJ (2014) Putting a spin on jatropha: How conservationist rhetoric drove Bedford Biofuels out of Tana Delta-Kenya. Sustainability 6: 2736–2754

Kronen M, Stacey N, Holland P, Magron F, Power M (2007) Socio-economic fisheries surveys in Pacific Islands: a manual for the collection of a minimum dataset. Secretariat of the Pacific Community, New Caledonia. 143 pp

Kronen M, Pinca S, Magron F, McArdle B, Vunisea A (2012) Socio-economic and fishery indicators to identify and monitor artisanal finfishing pressure in Pacific Island countries and territories. Ocean & Coastal Management 55: 63-73

Kumar A, Narayana AC, Jayappa KS (2010) Shoreline changes and morphology of spits along southern Karnataka, west coast of India: A remote sensing and statistics-based approach. Geomorphology 120: 133-152

Leauthaud C, Duvail SS, Hamerlynck O, Paul JL, Cochet H, Nyunja J, Grünberger O (2013) Floods and livelihoods : The impact of changing water resources on wetland agro-ecological production systems in the Tana River Delta. Global Environmental Change 23 (1): 252-263

Lebrun D, Hamerlynck O, Duvail S, Nyunja J (2010) The importance of flexibility : An analysis of the large-scale Tana-delta irrigation project in Kenya , implemented under an Estate System. In: Calas B, Martinon CAM (eds) Shared waters, shared opportunities: Hydropolitics in East Africa. Mkuki Na Nyota Publishers, Nairobi. 294 pp

Mahdavi S, Salehi B, Granger J, Amani M, Brisco B, Huang W (2018) Remote sensing for wetland classification: A comprehensive review. GIScience & Remote Sensing 55 (5): 623-658

Maingi JK, Marsh SE (2002) Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. Journal of Arid Environments 50 (1): 53-79

Manyenze FH, Munga CN, Mwatete CM, Mwamlavya HM, Groeneveld JC (2021) Small-scale fisheries of the Tana Estuary in Kenya. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 93-114

Marzialetti F, Giulio S, Malavasi M, Sperandii MG, Acosta ATR, Carranza ML (2019) Capturing coastal dune natural vegetation types using a phenology-based mapping approach: The potential of Sentinel-2. Remote Sensing 11 (12): 1506

McClanahan TR, Castilla JC, White AT, Defeo O (2009) Healing small-scale fisheries by facilitating complex socio-ecological systems. Reviews in Fish Biology and Fisheries 19 (1): 33-47

Mireri C, Onjala J, Oguge N (2008) The economic valuation of the proposed Tana Integrated Sugar Project (TISP) Kenya. Nature Kenya, Tana River. 72 pp

Mugabe ED, Madeira AN, Mabota HS, Nataniel AN, Santos J, Groeneveld J (2021) Small-scale fisheries of the Bons Sinais Estuary in Mozambique with emphasis on utilization of unselective gear. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 59-74

Munga CN, Ndegwa S, Fulanda B, Manyala J, Kimani E, Ohtomi J, Vanreusel A (2012) Bottom shrimp trawling impacts on species distribution and fishery dynamics; Ungwana Bay fishery Kenya before and after the 2006 trawl ban. Fisheries Science 78 (2): 209-219

Munga CN, Mwangi S, Ong'anda H, Ruwa R, Manyala J, Groeneveld J, Vanreusel A (2013) Species composition, distribution patterns and population structure of penaeid shrimps in Malindi-Ungwana Bay, Kenya, based on experimental bottom trawl surveys. Fisheries Research 147: 93-102

Munga CN, Mwangi S, Ong'anda H, Ruwa R, Manyala J, Groeneveld J, Vanreusel A (2014a) Fish catch composition of artisanal and bottom trawl fisheries in Malindi-Ungwana Bay, Kenya: A cause for conflict? Western Indian Ocean Journal of Marine Sciences 13 (2): 31-46

Munga CN, Omukoto JO, Kimani EN, Vanreusel A (2014b) Propulsion-gear-based characterisation of artisanal fisheries in the Malindi-Ungwana Bay Kenya and its use for fisheries management. Ocean & Coastal Management 98: 130-139

Munga CN, Kimani E, Ruwa RK, Vanreusel A (2016) Species composition of fisheries resources of the Tana and Sabaki Estuaries in the Malindi-Ungwana Bay Kenya. In: Diop S, Scheren P, Machiwa JF (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 329 pp

Muraguri P, Gioto V (2013) Tana River County short rains 2013-2014 assessment report. Kenya Food Security Steering Group (KFSSG), February 2014. [https://reliefweb.int/sites/reliefweb.int/files/resources/2013-2014%20SRA%20Report_Final.pdf]

Mwangudza P, Mlewa C, Munga CN (2016) Evaluating the fisheries potential of solar salt works reservoirs at Ungwana Bay, North Coast Kenya. Western Indian Ocean Journal of Marine Sciences 16 (1): 61-71

Mwaguni S, Ruwa RK, Odhiambo-Ochiewo J, Osore M (2016) Integrated water resources management in a changing climate: the implication of anthropogenic activities on the Tana and Athi/Sabaki Rivers water system for sustainable development. In: Diop S, Scheren P, Machiwa JF (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 329 pp

Ochiewo J (2006) Harvesting and sustainability of marine fisheries in Malindi-Ungwana Bay, northern Kenya coast (report no: wiomsa/marg-i/2006 – 03). Kenya Marine and Fisheries Research Institute [http://41.89.141.8/kmfri/bitstream/123456789/302/1/Sustainability%20of%20Marine%20Fisheries%20in%20Malindi-Ungwana%20Bay%20in%20Kenya.pdf]

Odhiambo-Ochiewo J, Ruwa RK, Osore M, Mutiso D, Mwaguni S (2016) The socioeconomic causes and impacts of modification of Tana River flow regime. In: Diop S, Scheren P, Machiwa JF (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 329 pp

Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. Science 325 (5939): 419-422

Pontius RG (2000) Quantification error versus location error in comparison of categorical maps. Photogrametric Engineering and Remote Sensing 66 (8): 1011-1016

Pricope G, Mapes NL, Woodward D (2019) Remote sensing of human–environment interactions in global change research: A review of advances, challenges and future directions. Remote Sensing 11 (23): 2783 [doi.org/10.3390/rs11232783]

Santos J, Groeneveld JC, MacKay F, Munga CN (2021) A regional assessment of seasonal-to-decadal changes in estuarine socio-ecological systems in the Western Indian Ocean region. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 131-xx

Scheren P, Diop S, Machiwa J, Ducrotoy JP (2016) The Western Indian Ocean: A wealth of life-supporting ecosystem goods and services. In: Diop S, Scheren P, Machiwa JF (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 329 pp

Shaghude YW, Wannäs KO, Lundén B (2003) Assessment of shoreline changes in the western side of Zanzibar channel using satellite remote sensing. International Journal of Remote Sensing 24 (23): 4953-4967

Smalley R, Corbera E (2012) Large-scale land deals from the inside out: findings from Kenya's Tana Delta. The Journal of Peasant Studies 39 (3-4): 1039-1075

Sulu RJ, Eriksson H, Schwarz AM, Andrew NL, Orirana G, Sukulu M, Beare D (2015) Livelihoods and fisheries governance in a contemporary Pacific Island setting. PLoS ONE 10 (11): e0143516 [doi.org/10.1371/journal.pone.0143516]

Terer T, Ndiritu GG, Gichuki NN (2004) Socio-economic values and traditional strategies of managing wetland resources in Lower Tana River Kenya. Hydrobiologia 527 (1): 3-14

van Beukering P, de Moel H, Botzen W, Eiselin M, Lange K, van Maanen E, van Weert, F (2015) The economics of ecosystem services of the Tana River Basin: Assessment of the impact of large infrastructural interventions. Institute for Environmental Studies, Amsterdam, Netherlands. 163 pp

van Sydow U (2002) Implementation of remote sensing for decision support systems. Proceedings from ISPRS Commission I Mid-Term Symposium in conjunction with Pecora 15/Land Satellite Information IV Conference on Integrated Remote Sensing at the Global, Regional and Local Scale. Denver, USA. ISPRS [https://www.isprs.org/proceedings/xxxiv/part1/paper/00047.pdf]