Received: 2 December 2023 | Revised: 2 July 2024 | Accepted: 5 July 2024

DOI: 10.1002/aqc.4229

ARTICLE

WILEY

Understanding the drivers of seagrass loss in Kenya: Evidence for the impacts of population and fishing

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Funding information
Sustainable Ocean Alliance (SOA)

Abstract

1. Seagrass ecosystems are crucial for supporting biodiversity and serve as vital fishing grounds. Unfortunately, their cover is declining globally. In Kenya, seagrass cover is falling by ∼ 1.6% annually but the causes are unknown. This study investigated the possible anthropogenic drivers of seagrass decline along the Kenyan coastline.
2. Satellite and large-scale geographic data on population growth, chlorophyll α trends, housing, and road density were used to explore their effects on seagrass cover loss along the whole coastline. Direct investigations were conducted into the effects of seine netting and basket trapping within seagrasses.
3. There was an average loss of 1.9 km^2 per 25 km^2 seagrass cover between 2000 and 2016 and a weak but significant relationship between population growth and seagrass decline, with losses concentrated in areas with the highest population density. In contrast with studies elsewhere, there was no evidence implicating eutrophication, supporting the suggestion that declines are linked to direct anthropogenic impacts such as fishing. A field experiment showed that a single instance of seine netting caused a significant loss of seagrass cover of 8.3% within the area fished, while no significant changes were observed with basket traps.
4. These findings support the evidence that declines in seagrass in Kenya and in other African countries are anthropogenic and are linked with fishing pressure and endorse existing efforts to restrict use of seine netting within seagrasses.
5. Understanding the status, changes, and drivers of change in seagrass ecosystems in Africa is crucial for developing effective national and local seagrass conservation plans, and for compliance with international commitments on seagrass conservation.

KEYWORDS

anthropogenic drivers, basket traps, eutrophication, fishing, population, seine netting

1 | INTRODUCTION

Seagrass meadows are one of the most ecologically rich and productive marine ecosystems (Duarte & Chiscano, 1999). They support humans and other species by supplying a wide range of services (Fourqurean et al., 2012; Githaiga et al., 2017; Hejnowicz et al., 2015; Waycott et al., 2009). Fishery production is the most prominent provisioning service, with seagrass beds providing habitat and nursery grounds for about 20% of the world's largest fisheries (Unsworth, Nordlund & Cullen-Unsworth, 2018), whilst also underpinning the livelihoods of millions of people in coastal communities engaged in artisanal and small scale fishing (Macreadie et al., 2017; Short et al., 2011), which is commonly practised in seagrass meadows (Cullen et al., 2007; de la Torre-Castro et al., 2014; Wallner-Hahn et al., 2022). Seagrass is easy to access and permits the use of a wide array of methods and gears (Jones et al., 2022; Vieira et al., 2020). In addition, seagrass meadows support a diverse range of fish and invertebrates that provide a reliable source of food across different seasons and years (Jones et al., 2022). Their importance as a fishing ground is evident from the high number of fish species associated with seagrass habitats. For example, in the Indo-Pacific region, seagrass meadows support 746 fish species, with 486 in Australia, 222 in the North East Pacific, 313 in the Caribbean, and 297 in the North Atlantic (Unsworth, Ambo Rappe, et al., 2018).

The meadows also provide food and shelter for thousands of other marine species, including endangered grazers such as dugongs, manatees, and sea turtles, while seahorses use them as their main feeding ground (Green & Short, 2003; Sievers et al., 2019; UNEP, 2020a). Seagrasses sequester significant amounts of carbon dioxide, accounting for up to 18% of the organic carbon buried annually in the oceans (Fourqurean et al., 2012; UNEP, 2020a). By filtering, cycling, and storing nutrients, sediments and pollutants, seagrasses help to maintain water clarity and purity; they may also reduce the abundance of pathogens capable of causing disease in humans and marine organisms (Lamb et al., 2017). By damping waves, slowing currents and trapping sediment, they can stabilize shorelines and reduce erosion (Green et al., 2021). These and other services mean seagrass meadows are very valuable ecosystems, with an estimated economic worth of up to US$ 34,000 ha^{-1} $year^{-1}$ (Short et al., 2011).

Despite these socio-ecological and environmental values, seagrasses are among the most threatened ecosystems on earth (Waycott et al., 2009). Due to their proximity to the shoreline and the scant awareness of their value by the fish-dependent communities, they are heavily impacted by human disturbance and pressures from urban and industrial development and agricultural intensification within the coastal zone have resulted in worldwide losses (Moreira-Saporiti et al., 2021; Short & Wyllie-Echeverria, 1996; Waycott et al., 2009). Globally, eutrophication is probably the most important cause of seagrass decline (Mvungi & Pillay, 2019; Waycott et al., 2009). Other anthropogenic drivers include physical disturbance (from, for example, dredging and boat anchors), diseases and urchin swarms (Alcoverro & Mariani, 2002; McClanahan et al., 1994) stimulated by eutrophication and over-fishing. However, much remains unknown about the status of seagrass ecosystems globally and if and why they are changing. For example, the influential work by Waycott et al. (2009), which estimated global rates of seagrass loss of 7% per annum, drew on a dataset that included only one small site in Africa. The primary aim of the current work is to determine which, if any, anthropogenic drivers are causing seagrass decline in Kenya, as a step towards filling this important gap in data from Africa as a whole.

Kenya supports approximately 317 km^2 of seagrass cover (Harcourt et al., 2018) comprising twelve seagrass species: *Halodule uninervis*, *Halodule wrightii*, *Syringodium isoetifolium*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Thalassodendron ciliatum*, *Zostera capensis*, *Enhalus acoroides*, *Halophila minor*, *Halophila ovalis*, *Halophila stipulacea*, and *Thalassia hemprichii* (Ochieng & Erftemeijer, 1993). As in other countries, the total extent of seagrass in Kenya is declining, with losses estimated at 1.6% per year since 2000 (Harcourt et al., 2018). Research into the possible drivers of seagrass decline in Kenya, or indeed in any African country, is sparse. A recent review found only 43 papers with any data on seagrass extent and/or drivers of change for the whole of Africa (Mwikamba et al., 2024). Only a single paper, reporting on Kenya, contained quantitative estimates of trends in seagrass across the whole country (Harcourt et al., 2018) with Mozambique, Tunisia and South Africa reporting trends in some parts of their coastlines. The most frequently cited potential cause for declines in African seagrass is fishing (Mwikamba et al., 2024). This contrasts with the dominance of eutrophication as the major cause in the global literature but is consistent with anecdotal reports, including observations using remote sensing of geometrical scarring in seagrass beds in Kenya (Harcourt, personal communication), and of large amounts of seagrass being dragged to the surface during fishing activities (Mwikamba, personal observations). The perceived damage caused by fishing activities such as seining is reflected in precautionary legislation (Government of Kenya, 2001), which often bans these practices even where there is no firm evidence of damage. The current work includes two different approaches. First, a country-wide analysis of satellite data explored large-scale evidence for anthropogenic drivers of seagrass change; seagrass is naturally variable, both spatially and temporally, so simply demonstrating changes over time, as in Harcourt et al. (2018) does not show anthropogenic effects. Second, having found an anthropogenic signature on seagrass decline, case study and experimental work were used to test the local (and by inference, regional) impact of specific fishing activities; fishing as a potential driver was chosen because of the published and anecdotal evidence of its likely impact.

Coastal fishing in Kenya is characterized by high fishing effort using multiple gears and practices, with a combination of *de jure*, *de facto* and open governance regimes (McClanahan et al., 1997). There is conflict among fishers (due to the high heterogeneity of fisher groups) and with other coastal users, with relatively poor state management and enforcement of regulations (McClanahan et al., 1997). This is exacerbated by changing fishing patterns (Tuda, 2019) as fishers from surrounding areas encroach onto sites traditionally used by the local communities. Although potentially damaging beach seining was banned in Kenya in 2001 (9th September 2001 Kenya Gazette notice No. 7565 (Government of Kenya, 2001), it persists in most areas along the coast because of limited enforcement, and perhaps because of a lack of understanding amongst fishers of the impacts it has (Karama et al., 2016; Okemwa et al., 2017). Perhaps because of its illegality, there is limited quantitative information on the extent of beach seining in Kenya. However, one study in Lamu estimated 32% of fish landings by weight were from beach seines (Karama et al., 2016).

Kenya is experiencing rapid population growth, estimated at 3.34% year^{-1}, which means that the population will double in ~21 years, and rates of growth are even faster at the coast as people migrate from more arid areas (Government of Kenya, 2019). This has contributed to growing pressures on the fishery, with small-scale fishers on the coast increasing from ~9000 in 2004 to 13,400 in 2016 (Government of Kenya, 2016). It is also linked with multiple other changes, including the increasing density of roads, buildings and industrial and agricultural activities, all of which could have an impact on the seagrass beds.

The present study investigated evidence that (1) the recorded decline in seagrass in Kenya is anthropogenic; (2) the decline is caused indirectly by activities in the watershed; (3) two commonly used methods of fishing can cause direct damage to seagrass. Objectives 1 and 2 were applied across the whole coastline, using satellite and other large-scale geographic data. In the absence of suitable country-wide data and given the anecdotal evidence for fishing impact in Kenya and other African nations, objective 3 was directly explored, looking at the effects of beach seining (Swahili: *Nyavu za kukokota/Vuruta*) and trappings (*Malema*) in seagrass areas at one important site.

2 | MATERIALS AND METHODS

2.1 | Study sites

2.1.1 | Kenyan coastline (used for country-wide analyses)

Kenya's coast stretches for 640 km and has diverse natural features including coral reefs, mangroves, seagrass and mudflats. The country experiences a tropical climate with bimodal rainfall patterns; the long rains occur between March and May and short rains between November and December. The alternating southeast and northeast monsoon winds influence sea conditions. The highest fishing activity takes place during the northeast monsoon (NEM) when the water is relatively calm and warm from November to March. The strong currents and rough water conditions during the southeast monsoon (SEM) restrict most small-scale fishing to shallow nearshore fishing grounds, especially in seagrass areas. Sea surface temperature is generally higher during the NEM season, fluctuating between 27 and 30°C, while lower temperatures between 24.5 and 25.8°C are recorded during the SEM (Wanjiru et al., 2023). Most coastal fishing is artisanal, multi-gear and largely unregulated (McClanahan et al., 1997; Samoilys et al., 2011).

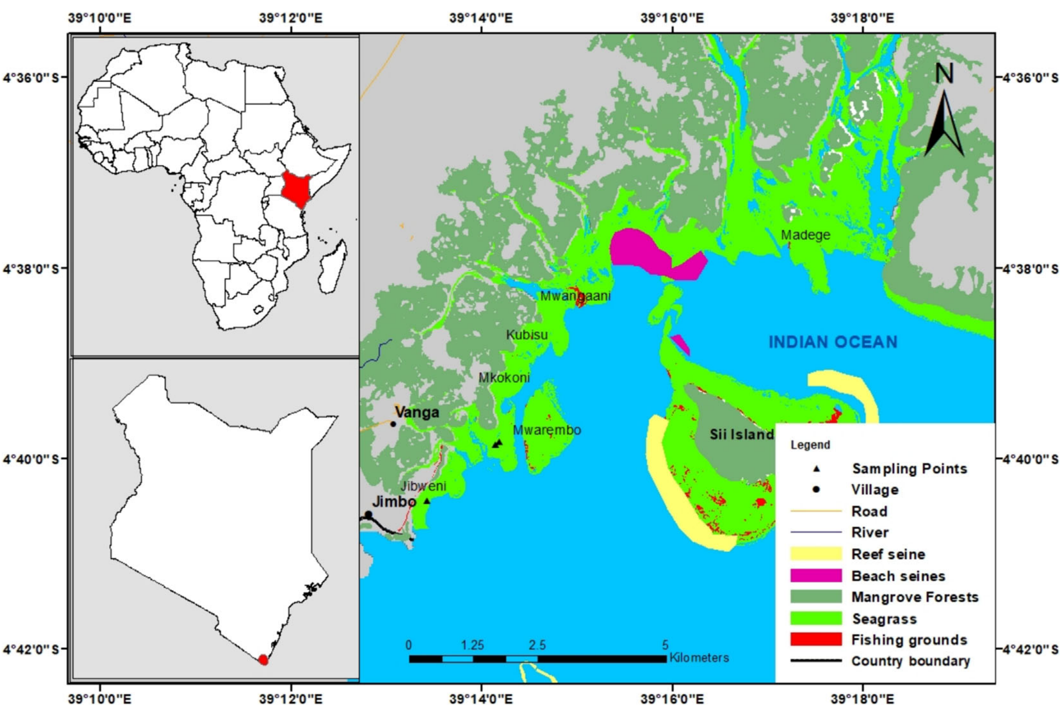

FIGURE 1 Major fishing sites in Vanga Bay and the sampling points of seine netting. The map was created using stakeholder consultations to map the fishing zones within the bay.

Vanga Bay (used for fishing experiments and observations)
Vanga is in southern Kenya and falls within the Kenya-Tanzania Transboundary Conservation Area (TBCA) (Figure 1, (4° 39′38.42″ S, 39° 13′ 9.71″ E).). The TBCA supports various economic activities, including fishing, subsistence agriculture and forestry (Fortnam et al., 2021). The community relies on fishing as the main source of food and livelihood, and there is evidence of increasing pressure on stocks, with a decline of ~40% in landings over the past decade (Fortnam et al., 2021). Fishing is mostly small-scale and artisanal.

2.2 | Seagrass cover change data

Kenyan seagrass cover for 2000 and 2016, based on analysis of Sentinel 2 satellite data, was obtained from the Dryad repository associated with Harcourt et al. (2018). For analysis, the Kenyan coastal area was divided into 5 × 5 km polygons centred on the coastline. Seagrass areas were clipped to these polygons, and a 5-km influence zone (buffer), surrounding seagrass in each polygon, was created to analyse the impact of the anthropogenic factors detailed below. To calculate the absolute change in seagrass cover for each polygon, the change was normalized by dividing it by the polygon's area and multiplying it by 100. This normalization method was employed to prevent the assumption that areas with no seagrass cover in 2000 and later found to have seagrass in 2016 underwent a full 100% change in cover.

2.3 | Selection and analysis of potential anthropogenic drivers

Possible predictor variables were selected based on evidence of their impacts from the global literature as well as the availability of sufficiently detailed data. A lack of suitably resolved data meant that some obvious putative drivers, such as land use change, could not be directly explored. Human population was taken as the foundational putative driver, with three other variables taken to indicate possible effects of human activity on watershed quality, with indirect impacts on seagrass.

2.3.1 | Changes in population density

Two raster layers representing population data for the years 2000 and 2016 were obtained from the WorldPop database (WorldPop, 2018) — population counts for Kenya. The raster layers were first converted to the WGS 1984 UTM zone 37 south coordinate system. They were then clipped to the Kenyan coastline using a vector layer representing the coastal area. Zonal statistics in QGIS (QGIS Development Team, 2023) were utilized to calculate the mean population density for each site, and then, subsequently differences in mean density between the two times were calculated for each seagrass site.

2.3.2 | Chlorophyll α trend

Chlorophyll α trend data (from 1997 to 2020) were downloaded from European Space Agency Ocean Colour Climate Change Initiative (ESA OC-CCI) (2023). The layer is derived from the fifth version of the global climate quality chlorophyll time series generated by the ESA OC-CCI (Sathyendranath et al., 2019). This uses time-series analysis to extract trends from seasonal cycles, and the linear trend is expressed as a percentage per year. Full details of the method can be found in Vantrepotte and Mélin (2009). As with population density, mean values for each seagrass buffer area were calculated. Since remotely sensed chlorophyll α data are mostly for open ocean areas, the values were not available for many of the areas immediately adjacent to the coast, and the sample size for analysis was therefore reduced.

2.3.3 | Road network density

Road network data for 2016 were downloaded from Humanitarian Data Exchange (2023b). Road network density within each site was calculated as the total length of the road within the buffer area in metres per square kilometre.

2.3.4 | Kenyan coast buildings

The 2016 Kenya building data were downloaded from Humanitarian Data Exchange (2023a). Building polygons were converted into centroids, clipped to the buffer areas and building density (buildings per km^2) derived. For both the building and road data, no temporal information is available to allow assessment of change, so effects were evaluated based on the situation in 2016.

2.3.5 | Data analysis

Data were analysed using the R statistical program (R Core Team, 2018). Linear models assessing the effects of different combinations of the predictor variables were constructed; log $(x + 10)$ transformation was used for population change owing to the distribution (some negative values), and road and building density were also transformed using log $(x + 1)$ transformation, to improve model fit. Multicollinearity between predictors was assessed using the variance inflation factor (VIF) in the *car* package of R (Fox & Weisberg, 2019), with variables excluded if VIF exceeded 5. The best-fit model was chosen using the Akaike information criterion (AIC), and Akaike weights (w_i) were also calculated to assess the relative support for different models fitted. Following the identification of the best-fit model, to assess the influence of spatial autocorrelation, an alternative model was constructed using the same predictors, and also incorporating an exponential spatial error term. Any change in fit was assessed using a likelihood ratio test based on generalized least-squares fit using the *nlme* package (Pinheiro et al., 2023).

2.4 | Impacts of fishing on seagrass cover

Seine nets and basket traps are the most commonly used gears within the seagrasses of Kenya, despite a formal ban on the former (Samoilys et al., 2011). Hence, they were the focus of the site-based studies.

2.4.1 | Seine netting experiment

Three 25-m-long transects, separated by a minimum of 50 m, were established and marked using buoys within a subtidal seagrass area with similar species composition (4.66°S, 39.23°E; Figure 1); all transects ranged from 3 to 5 m deep at spring low tide. Photographic video/image acquisition was done using a Go Pro Hero 4 camera during the field surveys. The camera features a 12-megapixel sensor and is equipped with a fisheye lens with a fixed focus whose nominal focal length is 2.9 mm. The camera was used with an acrylic waterproof housing (Rende et al., 2022). Fishing was done using a seine net of 30 m in length, 5 m in width, and a mesh size of 10 mm, fitted with assorted weights. The net was deployed from a boat by a team of 10 local fishers who were instructed to use their net as they would during normal fishing outings, for a single sweep per transect (Figure 3(b)). Prior to conducting the seine net experiments, permission was obtained from the Beach Management Unit and Kwale County fisheries office in Vanga.

To record seagrass coverage, a diver maintained a consistent distance of 1 m above the seafloor while swimming along each transect at a speed of approximately 20–25 m/min. The diver recorded continuous video footage before and after the seining process, with the camera positioned in a nadir orientation, capturing a view directly below. A guider diver swam in front of the cameraman towards the direction of the buoys, to ensure that the same area was captured before and after the seining process. Due to increased turbidity after seining, the diver waited approximately 5 min for the water to clear before capturing images after seining. Any seagrass material found within the nets was collected, identified and matched with the existing species in the transect. The materials were then oven-dried at 60 °C for 72 h, and their biomass determined to the nearest 0.1 g. The transects contained mixed seagrass species, and no attempt was made to separate species for analysis.

2.4.2 | Basket trap survey

Twenty-two seagrass sites that were being used by local fishers for basket trapping (Figure 4(b)) were identified with the help of the fishing gear surveys by the Kenya Marine and Fisheries Research Institute (KMFRI). These sites were not manipulated experimentally, rather they represented all the available basket traps being used in Vanga and Gazi Bays. Gazi (4.44°S, 39.50°E) is a similar site to Vanga, 20 km north, with the same seagrass species present (Githaiga et al., 2017). Because of poor visibility, images from nine of the traps could not be used, leaving five of those operated at Vanga, in seagrass adjacent to the area used for the seine netting experiment, and nine from Gazi. The identification process involved the consent and assistance of basket trap fishers. Each trap was slowly lifted, and an image was captured in the exact area where the trap had been originally placed. Another image (control) was captured adjacent to the area which was under the trap. This allowed for a comparison of the seagrass cover between the area which was under the trap and the adjacent area which was uncovered by the trap, to act as a control.

2.4.3 | Image extraction, preparation, and data analysis

For the seine fishing assessment, video footage was initially trimmed to extract just the 25-m transect. To assess changes in seagrass, cover along the transect, matching frames were extracted from videos taken before and after seining based on the total swim time, video frame rate and field of view at a 1-m distance between the camera and seabed. Key details from the resulting videos, such as length in seconds (t) and frame rate (f), were recorded. These details were then used to calculate the frame extraction interval using the formula: Interval (i) $= v/(d/(f * t))$, where d is the transect distance and v is the visible distance in the field of view. In total, 76 frames were extracted and analysed from three transects in seine netting (34 for transect A, 26 for transect B and 16 for transect C; the number per transect varied due to marginal differences in swimming speed). For the impact analysis of basket traps, a total of 28 frames were analysed. To optimize processing time, the extracted seine net images were resized to a standard width of 600 pixels. Evaluations conducted on the downsized images indicated that there was negligible loss of image quality that did not affect the estimation of cover (Pearson correlation of cover from full resolution image against cover from downsized image, $r = 0.977$, $p < 0.00001$). For the basket traps, the image captured adjacent to the trap (control) and the other one where the trap was (impact area) were used.

For both seine net and basket trap images, the *pliman* package (Olivoto, 2022) was used to segment the images into seagrass and non-seagrass areas to calculate the total area in each image and convert it into percentage cover. Segmentation was based on the blue-green index method; alternative indices were assessed, but this method gave the best outcomes based on visual analysis of the segmented images. A paired t-test was employed to compare the seagrass cover values, paired by before and after images, to assess any cover change.

3 | RESULTS

3.1 | Area change

Kenya's seagrass cover was found to be declining from the year 2000 to 2016. On average, each 25 km^2 of seagrass area lost 1.9 km^2 over this time (Table 1), although of the 188 polygons analysed, 31.9% showed an increase in cover.

Human population density increased by 68.2% within the areas adjacent to seagrass between 2000 and 2016.

A summary of the results from the different models tested is given in Table 2. Chlorophyll α data had a lower sample size than the other variables as detailed in the methods. It showed no significant relationship on its own, and when modelled with the other variables, it showed very high collinearity and was thus removed from further analysis.

Based on the AIC values, the simplest model, with population density change as the sole predictor, was the best-fit model and the Akaike weights indicated that this had approximately twice the support of the next best-fit models. A comparison of the spatial and non-spatial versions showed that a spatial model was a significantly better fit to the data (likelihood ratio = 25.3, $p < 0.001$). There was a negative relationship between population density change and seagrass cover change (slope coefficient (± SE) −0.78 ± 0.3; Figure 2).

3.2 | Experimental seine netting

The mean (±SD) percentage of seagrass cover across all three transects before experimental seining was 44.4 ± 7.3%. Following the seining, the mean percentage cover declined to 36.1 ± 6.9%, a highly significant difference ($t = 8.9$, df = 37, $p < 0.001$). Among the three transects (Figure 3(a)), transect A exhibited an average seagrass cover change of 9.71 ± 5.72%, transect B showed a change of 7.57 ± 6.84% and transect C displayed a change of 7.30 ± 5.55%. The overall loss in percentage cover across all three transects was determined to be 8.23 ± 5.70%.

The seagrass biomass collected following seining was 11.1 ± 1.5 g dry mass per m^2; this is likely to be an underestimate since it is based only on the seagrass material that was retained within the net.

TABLE 1 Descriptive statistics for seagrass cover and potential drivers over the period considered.

Variable	Mean ± SD
Absolute seagrass cover (km^2 25 km^{-2}) 2000	2.1 ± 2.5
Absolute seagrass cover (km^2 25 km^{-2}) 2016	1.63 ± 2.0
Absolute seagrass cover change (km^2 25 km^{-2})	−1.89 ± 4.4
Average population density per km^2 in 2000	204.8 ± 540.4
Average population density per km^{-2} in 2016	344.4 ± 902.2
Average population density change per km^{-2}	139.52 ± 45.8
Road density (m km^{-2}) 2016	627.1 ± 983.5
Building density (houses km^{-2}) 2016	323.38 ± 934.6
Chlorophyll α trend (% change year^{-1})	−0.319 ± 0.9

Abbreviation: SD, standard deviation.

3.3 | Basket traps

The mean (± SD) percentage of seagrass cover in the areas under the trap was slightly highercompared to control areas (Figure 4(a)). However, there was no significant difference between them ($t = -0.6121$, df = 13, $p = 0.551$), regardless of species or area.

4 | DISCUSSION

The current work showed a significant, if modest, relationship between rates of population growth and seagrass decline across the whole coast of Kenya, suggesting the documented reduction in seagrass coverage in the country has anthropogenic drivers. One likely driver is destructive fishing, and the experimental results in this study show how a single session of seine netting can cause significant damage. Hence, these results support the frequent reporting of fishing as a major factor in the decline of seagrass across Africa (Mwikamba et al., 2024).

The status, recent changes, and drivers of change in African seagrass ecosystems are all poorly known. Apart from information from coarse-grained worldwide data sets (McKenzie et al., 2020), there are published data on seagrass extent from only 12 of the 41 African nations with coastlines (Mwikamba et al., 2024). Only one nation (Kenya) has quantitative estimates of change across the whole coastline, and discussion of the causes of any changes in Africa is mostly speculative and based on single sites. Notably, despite legislation outlawing the use of fishing gear such as seines within seagrass areas, there is, to our knowledge, no published evidence for damage caused by these gears in Africa. A better understanding of status, change and drivers in Africa will be important for the development of national and local conservation plans and the adherence to international commitments on seagrass conservation (Shilland et al., 2021). For instance, Kenya included seagrass ecosystems in its 2021 Nationally Determined Contributions

Model	AIC	Δ_{AIC}	w_i	R^2
Population change	1025.6	0.00	0.4595	0.036
Population change + road density	1027.1	2.50	0.2223	0.039
Population change + building density	1027.1	2.50	0.2195	0.039
Population change + building density + road density	1028.9	3.30	0.0899	0.040
Building density + road density	1033.5	7.90	0.0088	0.0039

TABLE 2 Model results for different combinations of predictor variables giving Akaike information criteria (AIC) values; difference in AIC values between models (Δ_{AIC}), Akaike weights (w_i) representing the relative support for different models, and Nagelkerke R^2 values.

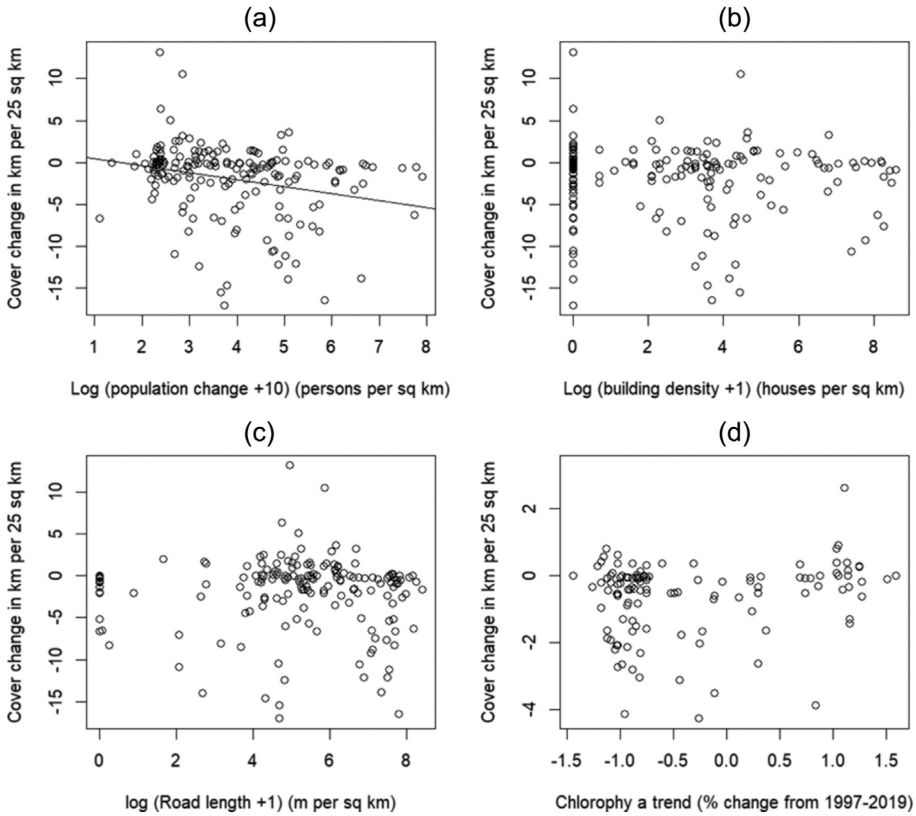

FIGURE 2 Population change (a), building density (houses per km^2) (b), road length (m per km^2) (c), and trends in chlorophyll α concentration (d) against seagrass cover change; (a) shows a significant relationship with a slope coefficient (±SE) of −0.78 ± 0.3.

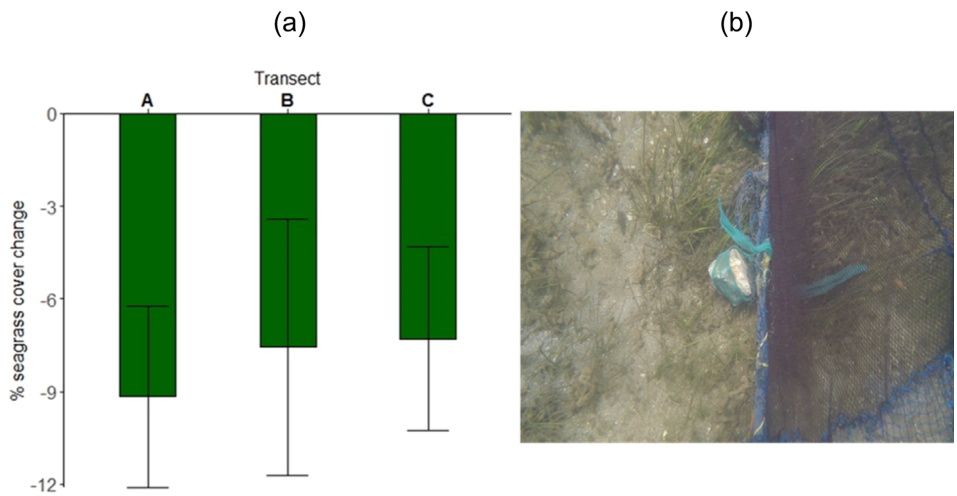

FIGURE 3 (a) Mean (± 95% CI) percentage seagrass cover change in three transects after seining. Means and CIs are from all frames within each transect. (b) Seine Net hauling during the experimental fishing. CI, confidence interval.

(NDCs) submission, which involves implementing measures for adaptation and mitigation (Government of Kenya, 2020). Consequently, Kenya will now need to create implementation plans to achieve these NDC targets.

Harcourt et al. (2018) demonstrated that across the whole Kenyan coastline, seagrass cover was declining (by 1.6% year^{-1}), but the causes of this change were unknown. Seagrass coverage may be patchy and dynamic, with natural fluctuations between years. In addition, some causes of longer-term trends, such as historical declines caused by seagrass wasting disease, were probably not linked to human activity (Graham et al., 2021) (although the relationship between disease and elevated water temperatures may implicate climate change in any future outbreaks). Hence, this study explored evidence that the changes in Kenya were anthropogenic in origin. The simplest (and arguably foundational) pertinent data are on population density. The significant, albeit weak, negative relationship between population growth and seagrass cover shown here supports this hypothesis, at least on a coarse scale. The areas adjacent to the major towns of Lamu, Malindi, Kilifi, Mtwapa, Mombasa and Vanga showed higher levels of seagrass cover loss (ranging from 2.8 to 4.1 km^2) than

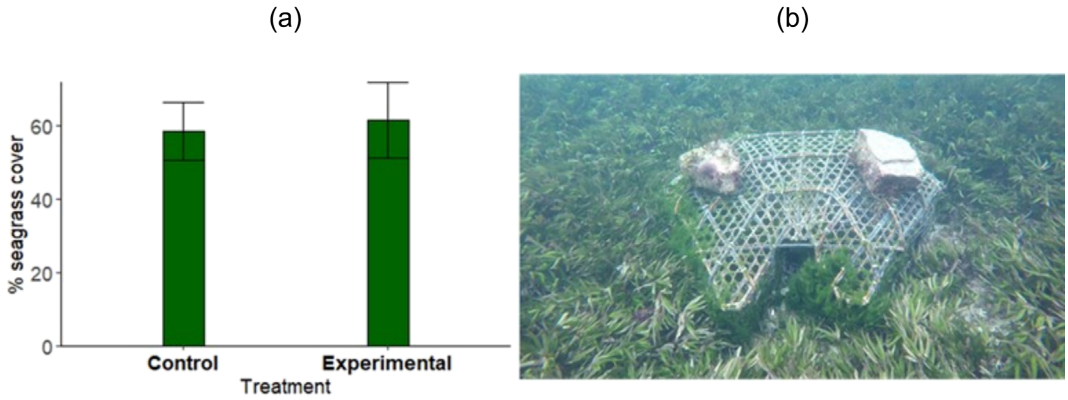

FIGURE 4 (a) Mean (± 95% CI) percentage seagrass cover within the control (areas without traps) and experimental (areas under the trap). (b) A basket trap as it was found in the field during field sampling. CI, confidence interval.

the average across the coast (1.89 km^2). Not all areas showed losses; 31% of the polygons containing seagrass recorded gains. However, these positive changes were generally small in area, often representing a change from bare sand to small new patches. Areas with gain were predominantly within shallow creeks while those with loss were in more open areas, possibly reflecting a difference in typical fishing pressures between these areas or synergies between seagrass and adjacent mangroves (Huxham et al., 2018). This evidence that seagrass decline in Kenya is linked to human activity is consistent with reports from across the globe (Purvis & Jiddawi, 2023; Waycott et al., 2009).

Eutrophication is cited as the single most important cause of global seagrass loss (Burkholder et al., 2007; Green et al., 2021; Green & Short, 2003; Short & Wyllie-Echeverria, 1996). In contrast with this global picture, no evidence was found here for a link between seagrass loss with chlorophyll α concentration. The impacts of agriculture could not be directly investigated, because of a lack of data. However, eutrophication is the major way in which agriculture negatively affects seagrasses, and hence, chlorophyll α should act as a proxy. Whilst the power of the analysis was limited by data availability (35% of polygons lacked data on chlorophyll α trends), the absence of even a non-significant negative correlation suggests that eutrophication may not be a dominant driver in Kenya and that other human activity, such as fishing, may be more important.

Models which combined road and building density with changes in population did not give better explanations in the current work. This supports the conclusion derived from the chlorophyll α analysis in suggesting that watershed impacts are not the most important drivers of seagrass decline in Kenya and that, instead, direct impacts such as fishing are relatively more important. Despite this, building density may act as a proxy for damaging human activities within the watershed. In Tampa Bay, Florida, increased urbanization, as measured by the density of buildings, was linked with a 47% decline in seagrass cover between 1950 and 1982 (Lizcano-Sandoval et al., 2022). Roads facilitate travel and opportunities to visit and exploit new and possibly undisturbed areas (Spellerberg & Morrison, 1998). For example, in Kenya, road density is a predictor of mangrove forest loss (Rideout et al., 2013) perhaps because roads permit easier extraction of wood.

The only published information on causes of seagrass decline in Kenya comes from Alcoverro and Mariani (2002) and Sergon et al. (2022) which describes the impacts of sea-urchin grazing on seagrass cover. Whilst other drivers, such as sedimentation, may well be important there is no available evidence. This data gap emphasizes the need for further work in this area.

4.1 | Impacts of fishing

The seine netting experiment, employing fishers using their usual gear at their familiar grounds, was designed as a small-scale simulation of the pressures experienced along the Kenyan coast. The nets could damage seagrass in several ways, including by tangling fronds in rope, dragging sinker weights over roots and suspending sediment that causes problems with turbidity. The use of seine nets removed approximately 11.1 gm^{-2} (about 5.4%, based on the average aboveground biomass values given in Githaiga et al. (2017)) of aboveground seagrass living material in one sweep. This removal will have negative impact on the seagrass fauna, including herbivores and grazers that rely on seagrass for food (Githaiga et al., 2019). Furthermore, this practice also diminishes the carbon sequestration potential linked to the ecosystem (Githaiga et al., 2017; Githaiga et al., 2019). In addition, small-scale fishing was found to have a negative correlation with percentage seagrass cover in Zanzibar (Purvis & Jiddawi, 2023). In terms of seagrass fauna, seine net fishing has also been associated with reductions in fish abundance, shifts in distribution of fish and alterations in ecological roles exercised by fish assemblages (Vieira et al., 2020). These predictable impacts provide the rationale behind the prohibition of seine netting in Kenya (Samoilys et al., 2011), but testing these effects is important, for the probity of policy and to help communicate to fishers why regulations should be observed. This is particularly the case in locally managed areas, such as the recently established in Vanga Seagrass Project (Association for Coastal Ecosystem Services (ACES), 2023). Clear and significant impacts from a single operation of a seine net were found in our experimental areas. These results support the policy and the anecdotal evidence that fishing is an important driver of seagrass decline, in Kenya and in other African countries (including Madagascar and Sierra Leone) where similar gears are used (Cheikh et al., 2023; Hantanirina & Benbow, 2013). Seining is already banned in Kenya; the challenge is one of compliance. In most areas, in Kenya as in other African nations, there are very limited resources from government to enforce compliance, so locally managed approaches which engage with fishers must be used. The current results can support public education and engagement in such projects.

Unlike seine nets, basket traps are a legal method of fishing in seagrass in Kenya; they are typically operated by subsistence fishers targeting high-value pelagic fish species. Whilst some of the traps we surveyed had obvious impacts, leaving areas of bare sand beneath them, such damage was not consistent, and overall, there were no significant effects of the traps. The aggregated impacts of traps will depend on their density and on how long they are left in place at a particular spot. A low trap density was recorded at the study sites, with a daily maximum of about five traps per hectare. Hence, little evidence is presented that basket traps might be driving seagrass declines in Kenya.

5 | CONCLUSION AND IMPLICATIONS FOR CONSERVATION

This research demonstrates a significant but relatively weak correlation between increased human populations and the loss of seagrass in Kenya, suggesting that the reported declines here are at least partly anthropogenic. As such, the pattern in Kenya conforms with that observed globally. However, it is suggested that the principle anthropogenic drivers here may be different from that most commonly found elsewhere, namely eutrophication (de Los Santos et al., 2019; Mvungi & Pillay, 2019). No evidence was found linking chlorophyll with declines. Instead, the site-based work supports the common assumption, embedded in policy and reported anecdotally in Kenya and other countries across Africa, that fishing activities are damaging seagrass. Whilst this work cannot establish the scale and degree of any fishing damage across the coast as a whole and does not exclude the influence of other possible drivers such as sedimentation or seaweed farming, it supports the current policy of banning seining (but allowing basket traps) within seagrass areas. Evidencing the difference between impacts from different activities may provide a resource for local communities working to manage their seagrass sites and looking for ways to communicate the need to differentiate between fishing gears employed. It demonstrates the need for further research on the important topic of how to support the sustainable use of the seagrass resources that are of such importance to millions of people in Africa.

AUTHOR CONTRIBUTIONS

Edward Mwikamba: Conceptualization; data collection; data analyses and writing—original draft; writing—review and editing. **Rob Briers:** Conceptualization; data analyses; writing—review and editing. **Michael Githaiga:** Conceptualization; writing—review and editing. **Mark Huxham:** Conceptualization; funding acquisition; writing—review and editing.

ACKNOWLEDGMENTS

We express our sincere gratitude to Kihawa Mohamed, the Vanga Beach Management Unit representative, for efficiently mobilizing the fishers, boats and nets for the seine net fishing experimentation. We extend special thanks to the basket trap fishermen in Vanga and Gazi villages for generously allowing us to utilize their traps for this survey. We acknowledge the kind cooperation of the fisheries department in Vanga, Kwale County, for permitting us to carry out the seine net experiments. We would like to thank Evans Nyanchoka, Gabriel Njoroge and Ben Ogola of KMFRI Gazi sub-station for their invaluable assistance during the field data collection process. This field activity was made possible through the generous support of a grant (Grant no: D008) from the Sustainable Ocean Alliance (SOA) awarded to Edward Mwikamba, and a fee waiver from Edinburgh Napier University.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data and R codes used are available from the authors upon request.

ETHICS STATEMENT

In Kenya, seine netting is a fishing method that is considered illegal, yet it is still routinely practised. However, before testing this method, we obtained formal permission from the fisheries department in Vanga, located in Kwale County. Additionally, we sought permission from the Vanga and Jimbo BMUs (Beach Management Units). As a result of the illegal nature of seine netting, the researchers sampled fewer but sufficient transects for statistical analyses.

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How to cite this article: Mwikamba, E.M., Githaiga, M.N., Huxham, M. & Briers, R.A. (2024). Understanding the drivers of seagrass loss in Kenya: Evidence for the impacts of population and fishing. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 34(7), e4229. https://doi.org/10.1002/aqc.4229