Western Indian Ocean J. Mar. Sci. Vol. 9, No. 1, pp. 57 - 73, 2010

Effects of Seismic Exploration on Mangrove Habitat in Tanzania

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Keywords: Mangrove, recovery, oil exploration, seismic survey, Mnazi Bay Ruvuma Estuary Marine Park, Tanzania, East Africa.

Abstract—Global demand for oil and gas has resulted in increased seismic exploration for new resources in environmentally sensitive areas. Reports of damage to ecosystem function have been reported, but the environmental effects of seismic exploration are largely undocumented. Key impacts in mangroves include tree removal and trampling. This paper reports on their effects in southeast Tanzania, through assessments of tree density and species distribution, incidence of local harvesting and changes in environmental conditions that might influence the biota. Seismic survey-related gaps in the canopy have not resulted in increases in mangrove recruitment, or affected microhabitat temperatures or salinity. However, seismic lines may have become access routes, leading to increased mangrove harvesting. There were few signs of recovery in the immediate vicinity of seismic lines, which appeared to be related to trampling effects on soil stability and changes in hydrology attributable to the loss of trees. Future research should target seedling and sapling abundance and growth rates, and soil structure, composition and nutrient levels. Recommended mitigation measures would involve the promotion of mangrove regeneration and the prevention of secondary impacts such as the use of lines as access routes, with monitoring of forest recovery.

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INTRODUCTION

Increasing global demand and rising prices for oil and gas have made it economically viable to prospect for new resources in areas that might previously have been thought politically or environmentally sensitive. Where coastal regions become the focus for such exploration, prospecting may take place in environments such as wetlands (Browning et al., 1996), salt marshes and mangroves (Osuji *et al.*, 2006; Osuji *et al.*, 2007).

Seismic surveying is one of the first stages in oil and gas exploration and is used to investigate an area's geological potential for resource discovery. The procedure involves the generation of low frequency sound waves and measuring their reflection from subsurface geological structures. These reflections are captured by geophone receivers and analysed to assess potential oil or gas resources. In mangroves, this involves the creation of seismic survey lines in which the vegetation is cleared from strips 1.5-2 m wide and holes are drilled for dynamite charges at ~50 m intervals.

Documented impacts of seismic surveys in mangroves include land clearance, drilling, explosions, noise, an influx of people, the creation of camps, and increased traffic (IUCN, 1993), but the environmental effects are largely undocumented. It has been suggested that surveys destabilise sedimentary material and increase turbidity, reducing photosynthetic activity (Zabbey, 2004), but very little scientific evidence has been presented illustrating ecosystem change. Two studies examined the impacts of 4D seismic exploration in the Niger Delta (Osuji et al., 2006; Osuji et al., 2007); both focused on chemical pollution and acknowledged that the results were affected by ongoing oil extraction, historical oil spills and the presence of base camps.

This paper reports on the effects of seismic exploration on mangroves in the Mtwara region of southeast Tanzania.

Field research took place in the Mnazi Bay - Ruvuma Estuary Marine Park (MBREMP) (Fig. 1), where gas reserves were first discovered in the 1980s. In 2005, a programme of 2D seismic exploration began and seismic surveys were undertaken in March 2005 and July 2007. In this study, the effects of seismic surveying on the mangroves were examined by comparing plots on seismic survey lines with adjacent plots located 20 m away, assessing: (1) the density and species distribution of trees in all age-classes, (2) the incidence of local mangrove harvesting, and (3) changes in environmental conditions that might have influenced the biota. In addition, the comparison of plots on the 2005 and 2007 seismic survey lines enabled an assessment of mangrove recovery rates.

BACKGROUND AND METHODS

The study area

A survey of coastal mangroves in Tanzania completed in 2000 identified 94.58 km^2 of forest in the Mtwara region, describing it as relatively unexploited and in better condition than other areas along the Tanzanian coast (Wang *et al*., 2003). The present study area fell in this region and is located in the south of the MBREMP near the village of Chui. It lies ~7 km inland, in the upper inter-tidal area, and includes an extensive channel and creek system but no major freshwater inputs. It forms part of the northern extension of the mangrove system in the Ruvuma delta 10 km to the south on the border with Mozambique (Fig. 1).

Field research was undertaken in two survey regions, one including a seismic line cleared in March 2005 (three years and two months earlier), and the other a line cleared in July 2007 (nine months earlier). The seismic lines studied run parallel to each other ~500 m apart and are ~1.5 km (2005) and ~2 km (2007) from the village of Chui (Fig. 2). Both regions support mixed stands of *Rhizophora mucronata* and *Ceriops tagal* and are inundated at high tides for between 15-30 days a month. *Avicennia marina* and *Sonneratia alba* occur seaward in the area, but were not recorded in the survey transects. The 2005 survey region was accessed on foot, while the 2007 region was reached in dugout canoes.

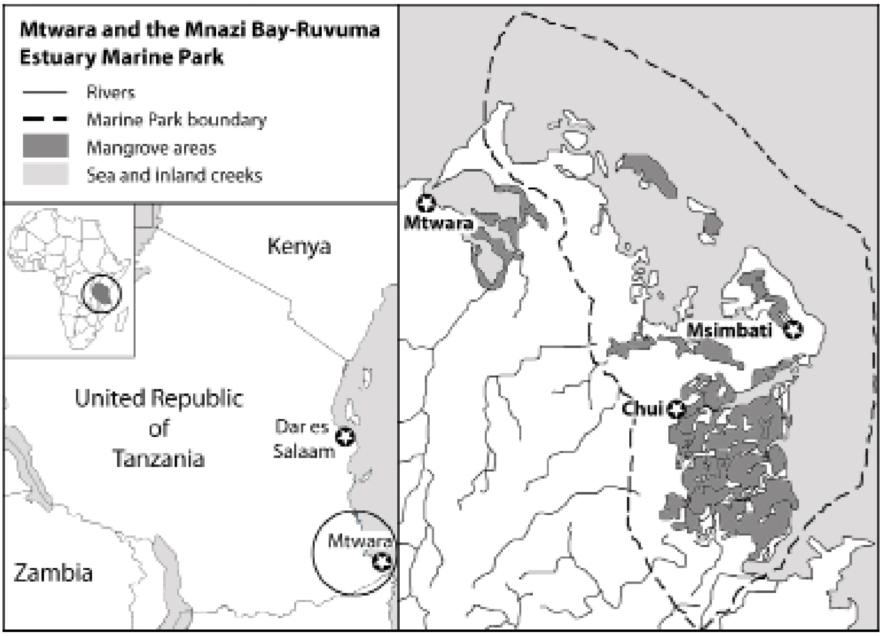

Fig. 1. Map of the study region with mangrove areas indicated by dark shading.

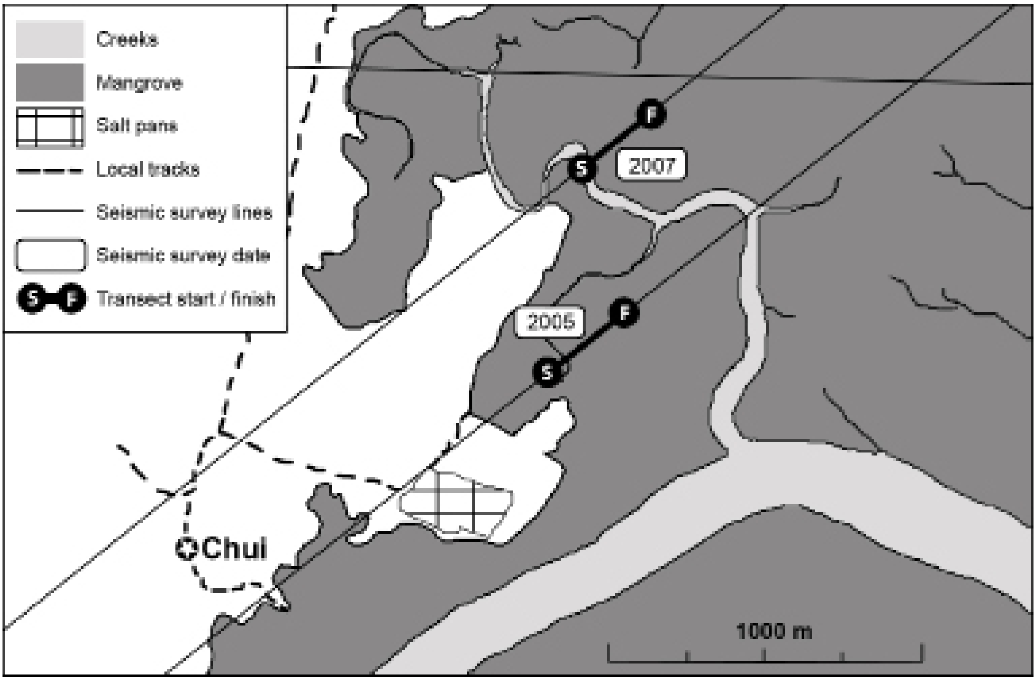

Fig. 2. Map of survey region showing the first (S) and last (F) plots on the 2005 and 2007 seismic survey lines.

Seismic survey procedures

Seismic survey procedures vary depending on the location and the scale of the operation. In sensitive environments such as mangroves, work is generally carried out on foot using a minimum of equipment. In the study area, each seismic line was traversed by at least six separate work crews (minimum crew numbers are given in brackets): surveyors and line cutters (8) defined the line and cleared vegetation; drilling crews (6-7) took a compressed air hose down the line and drilled holes for seismic charges; loading crews (4) laid charges; recording crews (10) laid geophones; shooting crews (4-5) laid detonators, possibly travelling the lines more than once to resolve problems; and, after firing, removal crews (10) cleared the area of equipment (Gwyther, A., Artumas Geophysical Operations Manager, pers. comm.).

We can thus assume that the seismic lines were ‘walked’ a minimum of 84 times (out and back) and, where lines were long and otherwise inaccessible, as is probable in larger areas of mangrove, crews may have again traversed ground they had already worked on in order to progress. This would have resulted in sections of line being walked 168 or 252 times if two or three passes were made. In addition, at 50 m intervals, drilling crews drilled shot holes, which then became the focus of subsequent work crews (Gwyther, A., Artumas Geophysical Operations Manager, pers. comm.), resulting in further trampling.

Field sampling and analysis

Site selection

Two 300 m transects were surveyed in each survey region, one with the seismic line running down the centre, and an adjacent transect 20 m away. Twelve 10 m x 10 m plots were located on each seismic line transect, six over shot holes and six between shot holes. From these, three plots of each type were selected for surveying using a random number generator. Plots on the adjacent transects mirrored the position of the seismic line plots. These 12 plots (six on each seismic line transect with their six adjoining plots) formed the basis of the mangrove and sediment surveys.

Within each plot, three 1 m x 1 m replicate quadrats were selected by dividing the plot into nine equal sections and randomly selecting one on each side of the seismic line (quadrats 1 and 3), and one on the seismic line (quadrat 2). A similar pattern of replicates was sampled in the adjacent plots. The replicates were used as loci for the measurement of mud temperature and pore water salinity and pH.

Survey times

Surveys were conducted over three four-day periods in 2008: 11-14 and 27-30 May, and 8-11 June. Seismic line transects were surveyed between 10:00 and 12:00 and adjacent transects between 12:00 and 14:00. All surveys were conducted shortly before or up to five hours after high tide.

General procedures

Surveying began at the start of each transect, progressing to a new plot each day to ensure that plots were not disturbed by the team prior to surveying. Quadrats and replicates were laid using coloured rope, sediment and water samples were collected, mud temperatures taken and mangrove surveys completed.

Mangrove surveys

Mangrove surveys focused on species diversity, density of seedlings, saplings and mature trees, and an assessment of their status and damage. Trees were counted within each plot, identified and categorised in the following age classes: seedlings, <1 m tall; saplings, >1 m tall but lower than the main canopy and without fully formed bark; and mature trees with fully formed bark near or within the main canopy. Trees were also categorised as living, damaged or dead, and the cause of any impacts was noted: seismic cutting, for cut trees within 0.5 m of the seismic line; other cutting, for cut trees >0.5 m from the seismic line; and unknown, for fallen, damaged or dead trees with no evidence of cutting.

Environmental variables

Environmental conditions were assessed by sampling sediment in replicate 2 in the mangrove plots. Mud temperatures were measured at the surface and at 10 cm in all the replicates, as were the salinity and pH of the pore water.

Sediment samples were collected to a depth of 10 cm using a corer 10.2 cm in diameter, bagged on site and sieved through 1 mm mesh under running water later the same day. Material retained in the sieve was placed in a 175 mm diameter dish and the percentage coverage of the total amount and the proportions of medium-coarse sand (>1 mm grain size), living root material, small living/dead root fragments, and plant debris was recorded.

Mud temperatures were measured with a non-mercury thermometer to an accuracy of 0.5°C. Pore water samples were collected by digging a shallow hole and allowing sufficient water to collect to fill sample bottles. Salinity was measured with a hand held refractometer to an accuracy of 0.5. Indicator solution and octet comparators were used to assess pH to an accuracy of 0.5, adjusted for salinity according to tables provided with the pH measurement kits (LaMotte Inc, MD, USA).

All samples were analysed in the evening on the day of collection, except samples from plot 5 of the 2007 survey, which were analysed the following day.

Statistical analysis

Data preparation

All data were tested using the Anderson-Darling Normality Test and Levene's Test for equal variance. Mangrove and environmental data that were not normally distributed were LOG10(x+1)-transformed and sediment data were arcsine transformed. In a small number of instances, data were used that passed Levene's Test but, in some data combinations, did not pass the Anderson-Darling Test. This route was taken as statistical analysis of variance is robust when dealing with non-normal distributions (Underwood, 1997). In such cases, Anderson-Darling results are given in the text.

Parametric tests

Analysis of variance was determined using Minitab Statistical Software (Minitab, 2007) for One-way and GLM-nested ANOVAs, the latter involving comparisons using Bonferroni's Pairwise Comparisons. Mangrove data were analysed according to tree density, species, age, damage status and damage impact, and retained sediment materials were analysed for quantity and relative composition.

GLM-nested ANOVAs employed the following nesting designs: [1] Region, Transect (Region); [2] Region, Transect (Region), Plot (Region, Transect); and [3] Region, Transect (Region), Plot (Region, Transect), Replicate (Region, Transect, Plot).

Regional differences

To ensure that differences determined between data sets were not a result of underlying differences between the two survey regions, additional analyses that excluded the effects of seismic clearance were conducted.

Tree populations were analysed by region with One-way ANOVA, and seismic clearance effects were excluded by combining living and dead trees in the analysis. The remaining data were also analysed by region with One-way ANOVA, but data gathered on seismic line transects were excluded.

Non-parametric tests

Data that manifested non-normal distributions and did not pass tests for equal variance were analysed using non-parametric Kruskal-Wallis tests in Minitab statistical software (Minitab, 2007).

Multivariate analysis

Parametric correlation analysis was not possible due to lack of homogeneity and non-normal distributions in the environmental data. Instead, principal component analysis (PCA) was carried out using PRIMER software (Clarke and Gorley, 2006). Sediment data were square root-transformed but temperature, salinity and pH variables were not manipulated. All variables were then normalised. A PRIMER Draftsman plot (Clarke and Gorley, 2006) suggested that none of the variables were significantly correlated, so all data were used for the PCA.

RESULTS

While the survey plan included twenty-four plots, tidal flooding prevented surveying of plot 5 on the adjacent transect in the 2007 region. Due to the missing data, line and adjacent plots 5 were omitted from both survey regions in the parametric analyses but incorporated in the multivariate analyses. Data from the mangrove surveys, sediment samples and environmental variables are summarised in Tables 1-3.

Differences between the two survey regions

Total tree densities (including living and dead trees) differed between the two survey regions ($p = 0.018$); *Ceriops tagal* was more abundant in the 2005 region ($p = 0.048$), but *Rhizophora mucronata* showed no significant difference. Within age classes, only mature trees manifested a difference between regions ($p = 0.004$), but a breakdown by species showed all age classes of *C. tagal* were more abundant in the 2005 region (mature trees $p = 0.045$, saplings $p = 0.008$, and seedlings $p = 0.030$).

Sediment analysis revealed that the total amount of material retained by the 1 mm sieve did not differ between the two regions but the 2005 transects had significantly more coarse sand than the 2007 transects ($p < 0.001$). Mud surface temperatures were indistinguishable between the regions. However, mud temperatures at 10 cm differed ($p < 0.001$), with the 2007 region having higher temperatures.

Kruskal-Wallis tests revealed salinity differences between the two survey regions ($p < 0.001$), with the 2005 transects exhibiting higher

Table 1. Condition and number of mangrove trees in the survey transects.

Tree condition	Living	Damaged			Dead			Total
Impact	None	Seismic	Local	Unknown	Seismic	Local	Unknown	
2005 seismic line	653	91	7	7	77	26	13	874
2005 adjacent plots	737	0	8	5	0	11	12	773
2007 seismic line	406	27	1	7	34	11	6	492
2007 adjacent plots	426	0	0	0	0	0	5	431

Table 2. Environmental variables recorded in replicate 2 in the survey plots.

2005 Seismic transect	Mud surface temp. (°C)	Mud temp. at 10 cm (°C)	Salinity	pH
Plot 1	27.0	26.0	35.0	6.73
Plot 2	26.5	25.0	30.0	6.74
Plot 3	28.0	24.5	29.5	7.24
Plot 4	25.0	25.0	33.0	6.73
Plot 5	23.5	24.0	33.0	6.73
Plot 6	23.0	23.0	33.0	6.73
2005 Adjacent plots				
Plot 1	26.5	25.0	32.0	7.23
Plot 2	27.0	25.0	31.0	6.24
Plot 3	25.0	24.0	31.5	6.73
Plot 4	28.0	24.0	34.0	6.73
Plot 5	25.0	24.0	33.5	6.73
Plot 6	22.0	22.0	35.0	6.73
2007 Seismic transect				
Plot 1	30.0	26.5	28.0	7.24
Plot 2	30.0	27.0	30.0	7.24
Plot 3	27.0	26.5	30.0	7.24
Plot 4	27.0	26.0	28.5	6.74
Plot 5	26.5	25.0	31.0	6.74
Plot 6	25.5	24.5	32.5	6.73
2007 Adjacent plots				
Plot 1	30.0	29.0	29.0	6.74
Plot 2	28.0	27.0	29.0	6.74
Plot 3	27.5	26.5	29.0	7.24
Plot 4	26.0	26.0	30.5	7.24
Plot 5	-	-	-	-
Plot 6	24.0	24.0	33.0	6.73

Table 3. Sediment composition recorded in replicate 2 in the survey plots.

2005 Seismic transect	Coarse sand	Living/dead root fragments	Living root material	Plant debris
Plot 1	0.33	0.22	0.11	0.33
Plot 2	0.43	0.14	0.43	0.00
Plot 3	0.43	0.29	0.14	0.14
Plot 4	0.33	0.22	0.33	0.11
Plot 5	0.29	0.14	0.29	0.29
Plot 6	0.20	0.40	0.00	0.40
2005 Adjacent plots				
Plot 1	0.33	0.17	0.50	0.00
Plot 2	0.43	0.14	0.29	0.14
Plot 3	0.29	0.43	0.14	0.14
Plot 4	0.17	0.50	0.17	0.17
Plot 5	0.22	0.22	0.33	0.22
Plot 6	0.20	0.30	0.30	0.20
2007 Seismic transect				
Plot 1	0.00	0.20	0.00	0.80
Plot 2	0.00	0.50	0.00	0.50
Plot 3	0.00	0.60	0.00	0.40
Plot 4	0.00	0.25	0.25	0.50
Plot 5	0.14	0.43	0.14	0.29
Plot 6	0.20	0.20	0.00	0.60
2007 Adjacent plots				
Plot 1	0.00	0.75	0.00	0.25
Plot 2	0.00	0.50	0.00	0.50
Plot 3	0.00	0.33	0.33	0.33
Plot 4	0.00	0.40	0.20	0.40
Plot 5	-	-	-	-
Plot 6	0.11	0.33	0.33	0.22

salinity levels, having a median of 33 compared to 30 in the 2007 region. The pH also differed between regions (Kruskal-Wallis p = 0.012), with the 2007 region having a higher median pH.

Differences between seismic lines and adjacent areas

Tree density and distribution

The number of living trees in the seismic line transects was not significantly different from the associated adjacent transects but there were more dead trees in the seismic line transects in both survey regions (nested ANOVA [1], 2005 $p = 0.030$, 2007 $p = 0.008$). In the 2005 region, 13% of the trees in the seismic line plots were dead compared with only 3% in the adjacent transect. Figures for the 2007 region were 10% and 1% respectively.

As expected, the number of trees manifesting damage from seismic clearing was greater in line transects than in the adjacent controls for both regions (Kruskal-Wallis $p = 0.005$ in each case). Seismic surveying resulted in a loss of 8.8% of trees in the 2005 line plots and 6.9% in the 2007 line plots. In addition, 17% of the living trees in the 2005 plots, and 10% in the 2007 plots had been damaged through the removal of branches or prop-roots during seismic surveying.

Living trees manifested no differences in density in terms of species, age class and combined species and age class variables in the corresponding seismic and adjacent transects.

Effects of local mangrove harvesting

Local cutting accounted for 3% of the dead trees along the 2005 line transect, 2.2% along the 2007 line transect, and 1.4% in the 2005 adjacent transect. No other cutting was evident in the 2007 adjacent plots. There were significantly more dead trees from other cutting in the 2005 line transect than in the 2007 adjacent transect (nested ANOVA [1], $p = 0.0353$).

Underlying environmental conditions

Sediment analysis yielded no significant difference in the amount of material retained by a 1 mm sieve between seismic line plots and adjacent plots. The composition of retained material was also similar; a regional difference in the amount of plant debris (nested ANOVA [1]; $p = 0.045$) was explained by a difference between the 2007 line transect the 2005 adjacent transect, these having the most and least of this material, respectively (nested ANOVA [1]; $p = 0.006$).

Mud temperatures at the surface and at 10 cm did not differ significantly between the corresponding seismic and adjacent transects. However, some data failed the Anderson-Darling test (mud surface temperature in the 2005 adjacent transect, $p = 0.010$; temperature at 10cm in the 2005 adjacent transect and 2007 line transect, $p = 0.032$ and $p = 0.042$). Corresponding plots manifested no significant differences in mud surface temperature, but the mud temperature at 10 cm for plot 1 in the 2007 region was lower in the seismic plot than in the adjacent plot (nested ANOVA [1]; $p < 0.001$). Analysis of the seismic survey transects comparing the different positions on the line (nested ANOVA [3]) yielded no significant differences in either temperature (but replicate 3 in the 2005 adjacent transect failed the Anderson-Darling test, $p = 0.039$).

Table 4. PCA results for the first three components of environmental variables.

Variable	PC1	PC2	PC3
Mud surface temperature	0.391	-0.368	0.134
Mud temperature at 10cm	0.404	-0.257	0.183
Salinity	-0.381	0.265	0.327
pH	0.343	-0.227	-0.266
Coarse sand in sediment	-0.407	-0.152	0.201
Root fragments in sediment	0.318	0.178	0.696
Living roots in sediment	-0.293	-0.523	-0.223
Plant debris in sediment	0.261	0.591	-0.442
% variation explained	57.7	17.9	9.4
Cumulative % variation	57.7	75.5	85.0

Kruskal-Wallis tests on salinity and pH yielded no significant differences between the seismic and adjacent transects.

PCA ordination of the environmental variables revealed relatively clear regional clustering, although the seismic and adjacent transects overlapped (Fig. 3b). The first three components listed in accounted for 85% of the environmental variation. The PCA ordination plot indicated that the sites are split by region at a Euclidian distance of 4, with all the 2005 sites grouping together (Fig. 3b). The association between the seismic line plots and adjacent plots was less clear. However, the majority of seismic plots fell in the area associated with plant debris in the sediment, and the majority of adjacent plots in the area associated with living roots in the sediment (Fig. 3a). The eigenvectors (Fig 3a) indicated that salinity, coarse sand and living root material in the sediment were the drivers of variation in the 2005 region, and mud temperature, pH, and plant debris in the sediment were the drivers of variation in the 2007 region.

Differences in mangrove post-seismic survey recovery

Apart from differences already presented in terms of regional variation, there were no significant differences between the seismic survey line transects in the two survey regions suggestive of differences in mangrove recovery.

DISCUSSION

Were there seismic-related differences in tree density and distribution?

Given the nature of seismic exploration in mangroves with its associated removal of all trees in lines ~2m wide, the greater number of dead trees in the seismic line transects was

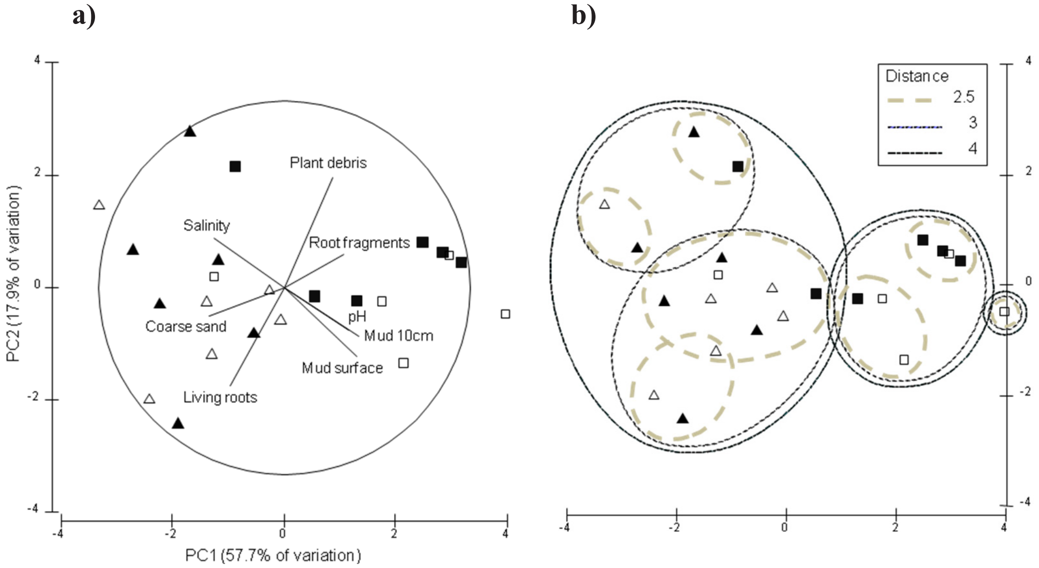

Fig. 3. PCA of environmental variables from the 23 mangrove plots. The depicted components account for 75.5% of the variation in environmental factors between plots. a) Eigenvectors indicate the direction and level that variables contribute to variation. b) Ordination plot clustered at various Euclidian distance similarity levels. (▲) 2005 seismic survey line, (△) 2005 adjacent plots, (■) 2007 seismic survey line, (□) 2007 adjacent plots.

expected. However, during surveying it was apparent that both areas had also been subjected to small-scale harvesting, and trees in this category were recorded separately. Although differences in the number of dead trees in the line transects were not significant, the higher percentage of trees affected by seismic impacts in the 2005 region may be an indication that environmental guidelines were less stringent at the time this line was created.

It has been suggested that canopy gaps in mangroves might play an important part in recovery from disturbance by improving survival rates and promoting increased abundance and growth rates (Clarke & Kerrigan 2000, Sherman *et al.*, 2000). However, despite the fact that vegetation clearance along the seismic survey lines had the effect of creating small canopy gaps, there were no significant differences in the number of seedlings and saplings in seismic line and adjacent plots in either region.

What was the effect of local mangrove harvesting?

Seismic survey clearance was not the only cause of mangrove damage. Cut stumps were recorded in line plots well outside the area of seismic survey clearance and in the surrounding areas of both survey regions. Cutting was focused particularly on the 2005 line transect, which was significantly different from the 2007 adjacent transect, indicating that the combined impact of seismic surveying and local cutting had resulted in a significant reduction in tree densities on the 2005 line.

The main target of cutting was *Ceriops tagal,* with *Rhizophora mucronata* being subjected to minimal damage. Both *R. mucronata* and *C. tagal* are target species for building materials, charcoal, boatbuilding, fish traps and firewood, and *C. tagal* is particularly favoured due to its termite-resistant properties (Muhando *et al*., 1999). Within the Mtwara district, 90% of the houses are built with mangrove poles and, in 1999, it was estimated that ~1600 mangrove trees were harvested annually, most without the proper authorisation (Muhando *et al*., 1999); mangroves in Tanzania are protected under the National Mangrove Management Plan (1994), which allows licensed harvesting by local residents for personal use, but not for resale.

The pattern of cutting suggests that seismic survey lines may have become access routes to the mangroves, facilitating harvesting from previously inaccessible areas. Cutting was highest in the 2005 region and the passage of time since its creation and its closer proximity to the village of Chui may have facilitated the greater damage. However, the 2007 line, created more recently, can only be reached by dugout canoe, yet had been subjected to more cutting than the 2005 adjacent line, suggesting that these factors were not the only influence. Instead, the lines appear to be targeted as they provide greater ease of timber removal afforded by the clearance. It is also possible that more remote areas are targeted when harvesting is illegal.

With no data on harvesting in the region prior to seismic surveying, it is not possible to establish if the creation of the seismic lines has resulted in increased harvesting or simply facilitated access to areas that could not be reached before. However, local community members confirmed that clearance lines were perceived as paths, and evidence of firewood collection was observed on the 2005 line transect during surveying.

Was there a change in the underlying environmental conditions?

The PCA ordination (Fig. 3a) indicated that, apart from mud temperature, sediment content was the next most important variable between regions and transects (Table 4), the main driver being the amount of plant debris in the sediment. This suggests that the seismic surveying may have resulted in compositional changes in the sediment.

Although mud temperatures did not differ between transects or within replicates, mean temperatures for replicate 2 of the line transects (the replicate on the cleared line) were consistently slightly higher, both at the surface and at 10 cm. Raised temperatures in mangrove mud have been shown to cause increases in salinity and nutrient concentrations due to increased evaporation (Kaly *et al*., 1997; Alongi & de Carvalho, 2008). However, salinity data did not reflect such a change. The gaps in the canopy created by the seismic lines may have been too small to cause a temperature rise, although this may vary with season; surveying took place at the end of the Tanzanian rainy season when temperatures were falling.

Was there evidence of recovery over time?

During surveying, it was noticeable that there were few seedlings and saplings in the immediate area of the seismic lines, despite the time difference in their clearance. Reasons for this are probably the trampling effects when the lines were originally cleared, ongoing trampling, and changes in the soil hydrology due to the loss of trees.

Trampling has been shown to break down the mangrove surface root layer and alter the structure of the mangrove sediments, and recovery from such impacts probably takes several years due to the slow growth rate of mangrove root systems (Dye, 2006). This loss of root material can also lead to a reduction in anaerobic conditions, resulting in reduced microbial activity, especially that of sulphate reducers (Alongi & de Carvalho, 2008), and increased levels of (toxic) sulphide, which inhibits seedling and mangrove growth (Hogarth, 2007).

In the PCA analysis, the position of individual plots relative to their sediment content showed that the 2007 seismic line plots were typified by dead, organic material that might have been generated during clearing, while the control plot sediments contained living root material. Many 2005 seismic line plots had neither. This suggests that, while some level of recovery may have occurred in the three years since seismic surveying, the surface root layer of the mangroves remained affected. Ongoing trampling and cutting would further hamper recovery by preventing seedling establishment.

Trampling also disrupts the surface topography and soil stability of mangrove mud and, combined with the loss of trees, can lead to increased tidal flushing, which slows down mangrove recruitment; seedlings are washed away before they become established if the soil lacks stability (Kaly *et al*., 1997; Kairo *et al*., 2001). Flushing can also result in reduced levels of nutrients (Kaly *et al*., 1997; Alongi & de Carvalho, 2008), and research on the effects of nutrients on Rhizophora mangle seedlings shows that phosphorous is a limiting factor in seedling development and, even when present, water-logged and anoxic soils render it ineffective (Koch & Snedaker, 1997). This suggests it may be necessary to artificially maintain

Fig. 4. The 2005 seismic survey line at plot 2 showing the path cleared between the mangroves.

soil profiles and increase nitrogen and phosphorus levels in damaged systems to aid their recovery (Kaly *et al*., 1997; Alongi & de Carvalho, 2008).

CONCLUSIONS

Areas cleared along the seismic survey lines in the study region had been subjected to additional local mangrove cutting. The combined effect of seismic clearing and local cutting was significant, but it was not possible to establish a link between canopy gaps and changes in seedling and sapling densities. It is possible that the more dispersed nature of local harvesting meant that the whole area was benefiting from increased light, but a lack of seedlings and saplings on the cleared lines suggested that this was not the case.

The present study was short in duration and based on a relatively small number of samples. Although some results were inconclusive, the seismic lines surveyed did not show signs of recovery (Fig. 4). Future research should target seedling and sapling abundance and growth in the lines, and soil structure, organic content and nutrient levels. This should elucidate any persistent effects of mangrove clearing and provide the information needed to develop appropriate mitigation measures to facilitate recovery. An assessment of local use of the mangroves might also establish the degree to which seismic lines are being used as access routes after their creation.

Future seismic surveys in mangroves need to incorporate monitoring of forest recovery, activities to promote regeneration, and the prevention of secondary impacts. Current guidelines specify that the area to be cleared should be minimal, mature trees should not be cut (the path should go around them) and branches should not be trimmed above the line of sight in an effort to retain the canopy (Artumas, 2008). They also specify the ‘blocking’ of access routes, but this appears to be directed at preventing vehicle access.

At present, vegetation cut during clearance is left at the side of the lines since its removal would exacerbate the environmental impact. It also acts as a barrier, discouraging access to the forest. This material could be replaced on and across the lines after surveying to create a more effective barrier to the area. This would have to be done over some distance to prevent its removal and make passage difficult, thus protecting mature trees in the centre of the forest.

Acknowledgements: This research was funded by Artumas Group Inc. I thank the following for their assistance: Dr M. Guard, Environmental Consultant to Artumas; H. Mkomba, for his invaluable knowledge of the seismic lines in the study region; and D. Reynolds and staff of the Mnazi-Bay Ruvuma Estuary Marine Park.

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