Acoustic Monitoring of Blast Fishing in Tanzania in 2018 and 2019

Final Report

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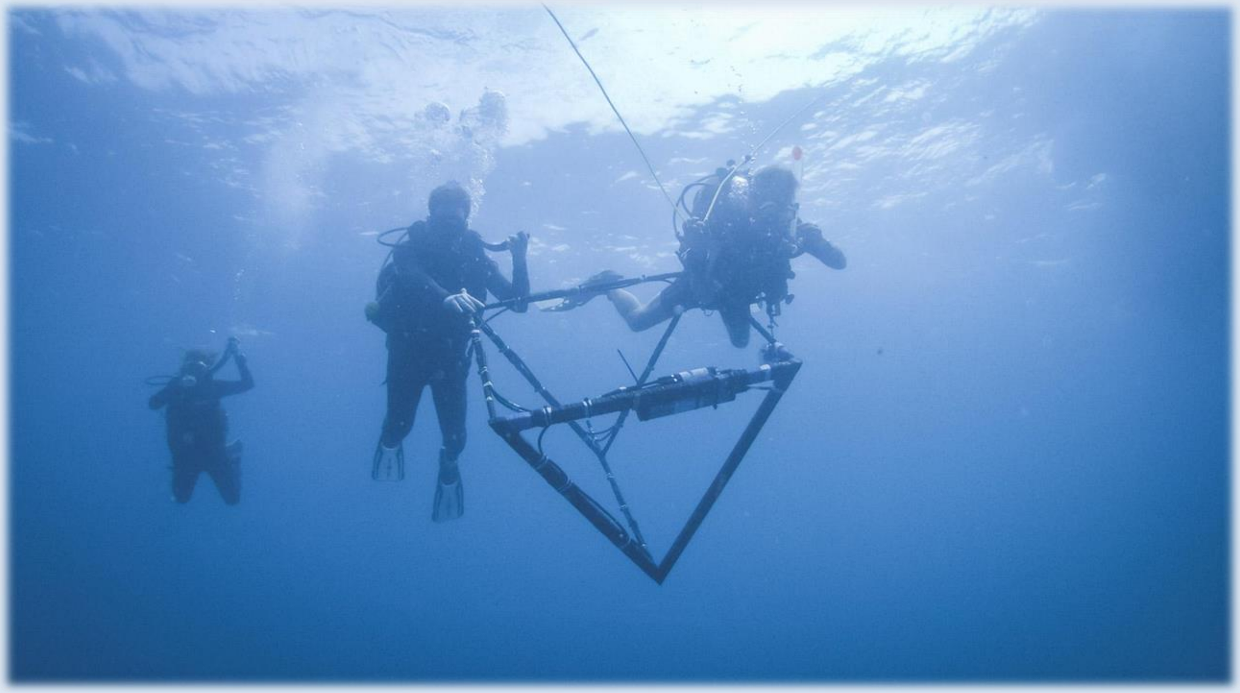

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Executive Summary

Since the 1960s fishing with home-made and, later, industrial explosives has been widespread throughout the coastal zone of Tanzania with large negative environmental and social consequences. Land-based monitoring estimated that in 2016 there were approximately 42,000 blasts at 24 hotspot locations along the Tanzania mainland coast. Government enforcement resulted in a substantial drop in blast fishing during the period 2016-2018, and since mid-2018 blast fishing levels in Tanzania have been at their lowest for decades. Gathering data on the location, timing and number of explosions over time is essential to be able to understand exactly when and where blasting occurs, to be able to guide enforcement into the right time and location, and to be able to monitor whether interventions have been effective. The overall goal of this current work was to use underwater acoustic monitoring stations to document the occurrence, and triangulate the exact location, of blast fishing explosions at key blasting hotspots in Tanzania. The acoustic monitoring was focused at four sites in two Tanzanian regions, Dar es Salaam and Tanga, both areas that have been subject to very high levels of blast fishing activity over many years. A total of 54 blasts (on a 50% duty cycle) were detected during 695 acoustic recording days between June 2018 and May 2019, giving an estimate of 108 blasts in total during that time period. A total of 49 blasts were recorded, and 98 blasts estimated to have occurred, in Tanga during the 279 days of acoustic recordings. By contrast off the coast of Dar es Salaam only 5 blasts were recorded, corresponding to an estimate of 10 blasts during 416 days of recordings over the same period. The recording location with by far the largest number of blasts detected was the area to the north of Pangani, towards Tanga Coelacanth Marine Park, where 80 blasts, representing 74% of the total were estimated. The majority of blast fishing activity occurred during the morning hours between 7am and 2pm and there was no preference for specific days of the week. Blast fishing occurred predominantly during low and falling tides (65% of detected blasts, n=35), and more than half (53.5%, n=29) of all blasts detected occurred during spring low tides. During extreme low tides it is easier to retrieve blasted fish (which generally sink) in the shallow, calm, low tide conditions, and also fishers are able to access deeper, less impacted and heavily fished habitats, thereby maximising their yields. When human land-based recorders and underwater acoustic recorders were deployed simultaneously, land-based recorders did not document a single blast, while the acoustic recorders continued to pick up small numbers of explosions. This suggests that in the face of increased enforcement blast fishers stopped blasting

in coastal areas, but continued in more remote locations, such as the seaward side of offshore reefs, out of ear shot of enforcement officials on land, where only acoustic recorders were able to detect them. Based on this study, it is concluded that the dramatic reduction in blast-fishing seen during 2016-2018 along the Tanzanian coast continued into at least the middle of 2019. However, blast fishing had not been completely eliminated and persisted at very low levels, particularly in offshore waters off the coast of Tanga Region. The frequency and pattern of blasts detected during this study suggests that only a very small number of fishing vessels (perhaps as low as one or two) are responsible for the residual blast-fishing effort in Tanga. The remnant blasting activity is in two areas: mainly off the outer reefs of Tanga Coelacanth Marine Park, and in offshore waters in the northern half of Mkinga District. It is recommended that for maximum effectiveness, enforcement agencies could focus effort on identifying and intercepting the vessels that continue to practice blast fishing by monitoring around the offshore reefs in the above-mentioned areas, during morning hours, especially during spring low tides.

Introduction

Background to Tanzanian Blast Fishing

Since at least the 1960's Tanzania has had an ongoing problem with the indiscriminate use of home-made and, latterly, industrial explosives for fishing (Rubens 2016, Slade and Kalangahe 2015, Wells 2009). Tanzania is the only country in East Africa or the Western Indian Ocean where this practice occurs (Burke *et al.* 2011). Fishing with explosives has been illegal in Tanzania since at least 1970 but challenges with law enforcement, and effective prosecution of offenders, mean that blast fishing has continued across nearshore waters of the Tanzania mainland coast for many decades. The practice has historically been much less prevalent in the Zanzibar islands, though the west coast of Pemba has been affected, in part possibly due to its relative proximity to Tanga.

Blast fishing is extremely destructive for the marine environment because each blast kills all living organisms within the radius of the explosion (1-2m) and in shallow reef areas the force of a blast also degrades corals, benthic organisms and the overall structural complexity of the sea bed that provides critical habitat for fish communities and related marine biodiversity. This takes decades to recover (Saila *et al.*, 1993; Alcala and Gomez, 1987), reduces the overall productivity of the coastal ecosystem and results in a highly degraded coastal zone and depleted fisheries (Fox *et al*. 2005, Fox *et al*. 2006). For example, in Tanga, fish densities were 12 times higher on a reef closed to fishing with little explosives damage as opposed to one nearby that was heavily impacted by blasts (Kaehler *et al.*, 2008). Blast fishing also has detrimental impacts on coastal communities; possession and deployment of explosives is hazardous and illegal, and it can cause conflict within villages between fishers who use legal gear and those that do not (Slade and Kalangahe 2015).

Gathering data on the location, timing, and number of blast fishing explosions over time has value for at least three reasons.

1. to quantify and communicate the scale of the practice to decision-makers.
2. to understand the spatial-temporal distribution of blasting in order to guide enforcement actions to the right places at the right time.
3. to monitor trends in blasting over time, and therefore understand whether enforcement actions have been effective or when the activity begins to increase again.

Historical Data on Blast Fishing

Prior to 2016, monitoring of blast fishing was *ad hoc,* informal and localised, coming largely from individuals who recorded the number of blasts that they heard, normally while they were undertaking other tasks in the coastal zone (Mwambao Coastal Community Network, 2016). For example, in the 1990s there were reported to be over 100 blasts on a single day on Mpovi Reef in Kilwa, and 440 blasts were heard in Mnazi Bay, Mtwara in 2 months (7/day) with a peak of 26 blasts in 3 h (8–9/h) (Guard and Masaiganah, 1997). During 2005-07, a small network of people in the coastal tourism sector south of Tanga City recorded blasts opportunistically during routine activities on land and at sea, often recording 20-50 blasts per month (unpublished data, Tanga Dynamite Monitoring Network). During a 15-month period from January 2014 to May 2015, two village beach management units (BMUs) in Kilwa (Songo Songo) and Mtwara (Mgao) recorded more than 11,000 blasts between them, with daily maximums of 90 in Songo Songo and 37 in Mgao (Rubens, 2016). During 2014-16, a coastal resident in Kigamboni District south of Dar es Salaam recorded blasts from his home on a daily basis, with gaps in some months, recording annual totals of 464, 481 and 400 and daily maximums of 20, 25 and 17, in the respective years (unpublished data, J. Lewis, Ras Dege).

Since 2014 there have been several efforts to collect more systematic data on blasting. A static acoustic recorder was placed in Mbudya Patches off Dar es Salaam for 6 weeks in early 2014, and recorded 438 explosions (on a 50% duty cycle) over the 46 days monitoring, giving an estimate of total 876 blasts during the monitoring period, and a mean blast rate of approximately 19 blasts/day (Cagua *et al.* 2014). The following year, in March and April 2015, 231 h (about 19 x 12 hour days) of acoustic data were collected from a boat based hydrophone array towed over almost 2700 km of systematically laid transects along the entire coast of Tanzania. A total of 318 blasts were confirmed using a combination of manual and supervised semi-autonomous detection. Blasts were detected along the entire coastline, but almost 62% were within 80 km of Dar es Salaam, where blast frequency reached almost 10 blasts/h (Braulik *et al.* 2017).

Monitoring and Enforcement since 2015

The years 2015 and 2016 witnessed some key turning points with regards to blast fishing monitoring and enforcement in Tanzania (World Bank/GoT, 2020). In particular:

- establishment of a government Multi-Agency Task Team (MATT) on environmental crime in June 2015, initially under the leadership of the Tanzania Police and latterly under the Vice-President's Office;
- financial support to the MATT for enforcement strategies was provided under the EU/IOC SmartFish programme;
- announcement of a zero-tolerance policy by President Magufuli in August 2016; and
- the start of a series of interventions against blast-fishing along the mainland coast by Tanzanian mainland government authorities which continued through 2016-18. These included intelligence-led enforcement operations under the auspices of the MATT, involving the Navy, the Fisheries Development Division of the Ministry of Livestock & Fisheries, the Tanzania Police, the office of the Director of Public Prosecutions (DPP) and others. In some southern coastal districts, assertions of authority by District Commissioners and district security committees were also effective;
- the Tanzania Blast Monitoring Network (TBMN) was launched on 1st May 2016, comprising a consortium of NGOs that organised land-based human recorders to monitor audible blasts at 24 hotspots in 13 out of 16 districts along the Tanzanian mainland coast.

The enforcement activities resulted in a dramatic reduction in blast fishing activity along the coast during 2017-2018. By the end of 2017, the TBMN reported that average monthly incidence of blast-fishing was reduced by 90% since high levels reported during middle of 2016. TBMN data showed that in 2016, 41,980 blasts were estimated across the 24 sites, in 2017 there were an estimated 9,565 blasts in the same area, and in 2018 this had reduced to just 465 blasts, with no blasts at all recorded during the final 4 months of the year (data from TBMN, (https://tz-blast-monitoring.net/blast) (See Fig 1. below).

Although blast fishing levels are the lowest they have been for 4-5 decades in Tanzania, previous experience has shown that if surveillance and enforcement efforts are not maintained blast-fishers will eventually reactivate their operations. Continuous monitoring is therefore important to be able to detect and combat that resurgence.

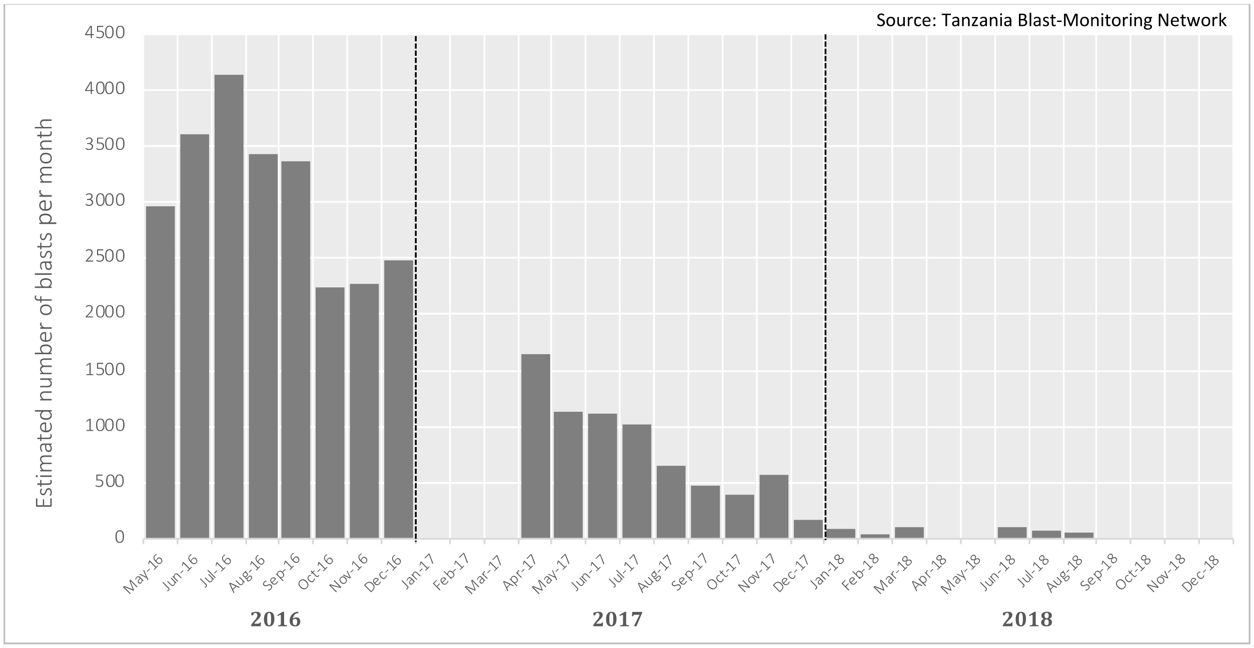


Figure 1 – Trend in estimated total monthly blasts at 24 hotspot locations along the Tanzania mainland coast based on systematic sampling from 01 May 2016 to 31 December 2018 (TBMN, (https://tz-blast-monitoring.net/blast)**.**

Comparison of Blast Monitoring Methods

During periods when government enforcement authorities are more active, blast fishing likely stops in easy to access and monitor coastal areas but continues on reefs or pelagic fishing grounds further offshore, out of sight and hearing of land-based monitors. Underwater acoustic monitoring is therefore a particularly appropriate tool in such circumstances, as the underwater acoustic signature of explosions can be heard from between 30 and 50km away (Woodman *et al.* 2003). The distinct advantages of acoustic monitoring versus land-based recorders are that a single acoustic device can monitor continuously, without needing to be attended, night and day, irrespective of the weather over many weeks. Because sound travels faster and further through seawater than through air, and acoustic recorders are more sensitive than a human ear, each acoustic recorder can monitor several thousand km^2 of ocean, including offshore areas that cannot be viewed or surveyed from land-based stations. However, acoustic units are costly to purchase and are prone to malfunction and loss at sea. Analysis is technical, requiring specialist expertise, and time-consuming, meaning that acoustic studies can be more expensive than land-based recording. Importantly also, is that with archival acoustic recorders there is a significant time-lag, between recording a blast and generating data, of up to 2-3 months or more. Conversely, land-based human recorders using widely available mobile phone technology can generate almost real-time reporting and, via a web-platform, deliver automated daily, weekly or monthly summary reports through a variety of data-delivery options including SMS messages or email reports. Technology exists for acoustic techniques also to deliver real-time reports, however that in turn substantially raises costs and operational challenges (Showen *et al.* 2018, Baumgarter *et al*. 2013, Miller *et al.* 2016). The constraints of using land-based recorders are that the 'field-of-view' or range-of-hearing is relatively small and nearshore (1-2km), and can be subject to either intentional or unintentional biases, error and human unreliability. The two monitoring approaches, acoustic and human land-based recorders are thus complementary, with land-based recording allowing near instantaneous information over a small area, and acoustic data providing more detailed, retrospective information on blast location over a much larger swath of ocean.

Project Objectives & Goal

The objectives of this work were as follows:

1. Use underwater acoustic monitoring stations to document the occurrence and triangulate the exact location of blast fishing explosions at key blasting hotspots in Tanzania over the course of one year;
2. Explore seasonal, weekly and daily variations in blast fishing activity at two different sites;
3. Examine the influence of tides and weather on blast fishing activity; and
4. Compare the number of blasts recorded by acoustic recording devices and land-based recorders to provide insights on the advantages and disadvantages of each method.

> *The overall goal was to determine whether blast fishing continues in Tanzania, document any resurgence in the activity, and identify areas and times where enforcement could be targeted to eliminate blast fishing.*

Methods

Study Design

Acoustic monitoring of blast fishing was conducted in two regions of Tanzania: Dar es Salaam and Tanga; both areas that have been subject to very high levels of blast fishing activity over many years (Braulik *et al.* 2017; Rubens 2016; Slade and Kalangahe 2015; Wells 2009) (Figure 2). Each recording station was configured such that it was possible to use the data collected to calculate a single unambiguous bearing to each detected blast. In open ocean, blasts may be detected by acoustic recorders up to 50km away, but complex and shallow bathymetry is likely to reduce that detection range considerably (Braulik *et al.* 2017, Woodman *et al.* 2003). In order to triangulate the exact location of blasts it was necessary to deploy paired recording stations, approximately 10km from each other; when the two stations simultaneously heard a blast it could be geolocated where the bearings from each unit crossed. With a 10km spacing between devices and accurate bearings expected from relatively broadband blasts (Woodman *et al.* 2003), it was expected that in open ocean conditions blasts could be geolocated out to at least 50km. Locations were selected for deployment that were not close to islands or fringing reefs so that they would be able to hear blasts across as wide a swath of the ocean as possible. Assuming a conservative 30km detection range for each recording station, each was able to monitor approximately 2800 km^2 of ocean.

Passive Acoustic Monitoring Hardware

Each recording station comprised a triangular 1m x 1m x 1m metal frame on which a 4-channel ST4300-STD SoundTrap acoustic recorder manufactured by Ocean Instruments New Zealand was mounted. The SoundTrap was connected to a 12V battery pack, and three low noise hydrophones (165dB, 30kHz Bandwidth), were attached to each corner of the triangular frame (Figure 3). The frame was encased in rubber to prevent abrasion of the wires, and all equipment was securely attached with electrical tape and zip ties to prevent vibration. Each recording station was dropped to the sea floor by divers using lift bags, was secured to three 50kg concrete blocks, and metal anchor stakes hammered into the seabed. Deployment locations were all in water 20-25m deep (Figure 2). Each SoundTrap was set to record at 36kHz on a 50% duty cycle, recording for 30 minutes out of every 60. The memory of each device (256GB) filled after 50 days on average and the units were retrieved, downloaded and redeployed with fresh batteries.

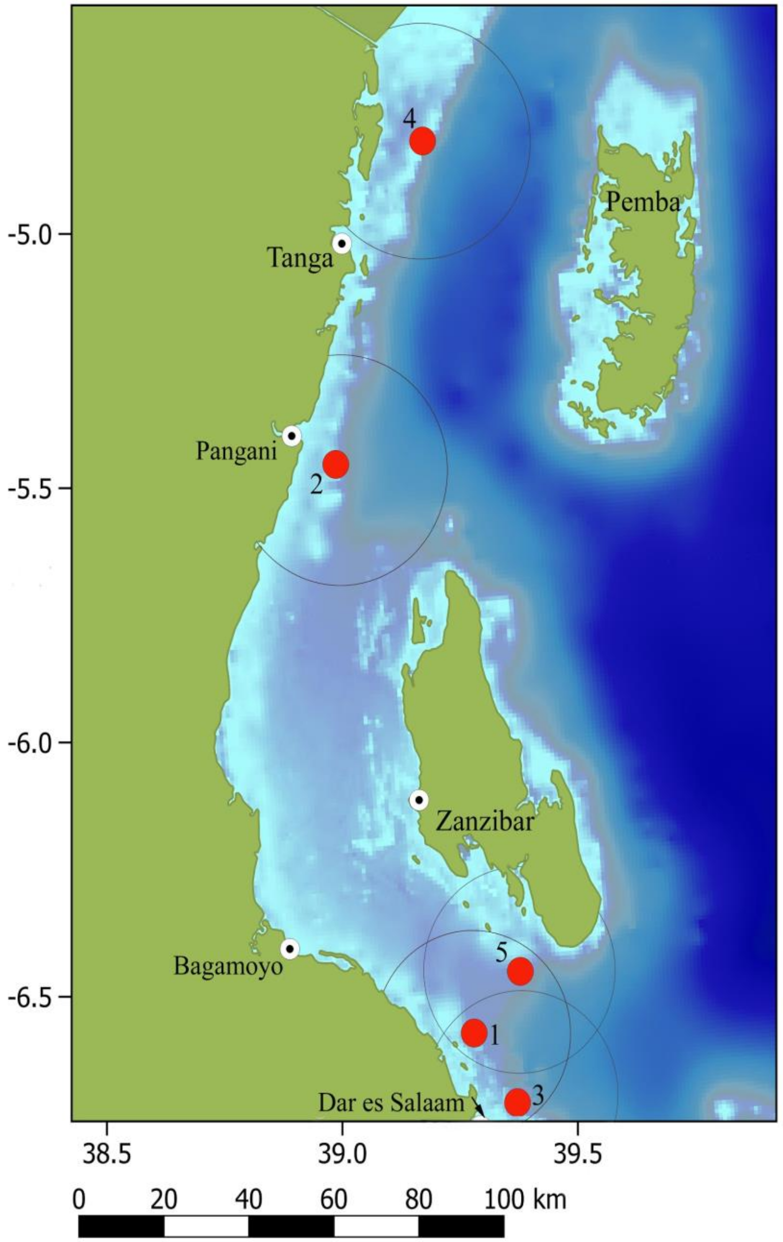


Figure 2 - Location of acoustic recorders deployed off the coast of Tanzania to record blast fishing explosions during 2018 and 2019. Red dots are the location of acoustic recorders, grey circles depict the approximate area monitored by the recorder (30km) and each unit was given a number which cross-references to the results in Table 1.

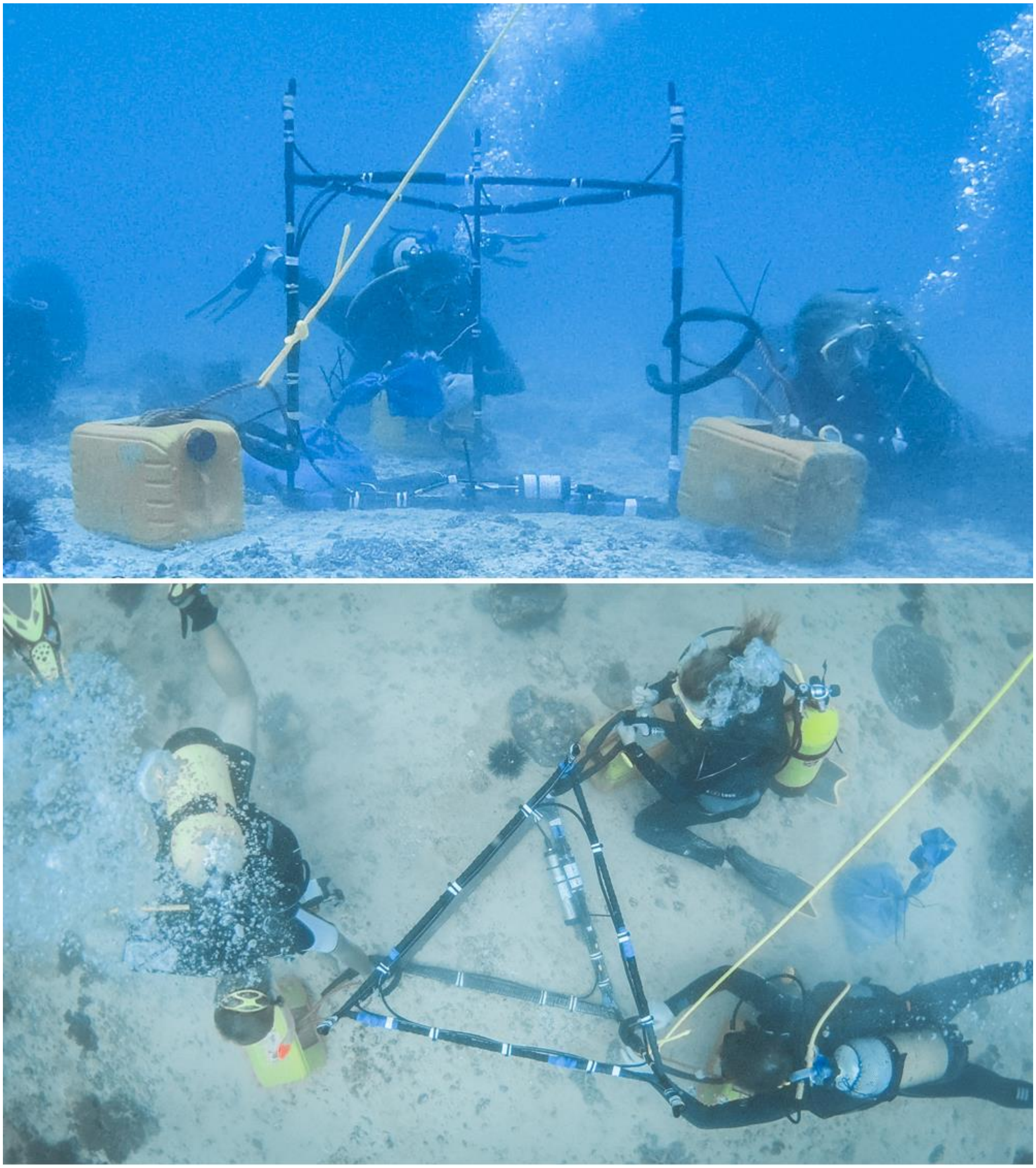


Figure 3 - Acoustic recording station deployment and configuration. The yellow cans are concrete filled weights, the hydrophones are located on the upper tips of the frame and the Soundtrap is visible attached to the centre bottom of the frame (Photo by Johnny Miller).

Acoustic analysis

Due to the quantity of data collected, manual analysis of the raw data was impossible and undesirable and the use of automated detection algorithms to identify bomb blasts was therefore a necessity. The advantage of automated detectors is that they are fast and generally consistent, however, they cannot deal with unexpected inconsistencies in datasets especially if there is a lack of data for training. Human analysts are slow but are excellent at pattern recognition and can recognise anomalies e.g. novel sounds. There was no readily available automated fish bomb detector software and only a few studies have described the temporal and spectral properties of fish bomb blasts in Tanzanian waters (Braulik *et al.* 2017, Cagua *et al.* 2014). The seas around Tanzania have not been extensively studied using passive acoustic monitoring and thus there was a high likelihood that there would be many unknown contributors to the soundscape which would trigger an automated detector. This lack of training data made the development of an accurate automated classifier, for example using deep learning e.g. Shiu *et al*. 2020, impossible. Therefore, for this dataset, a hybrid analysis approach was implemented. A relatively simple automated detector was developed based on previous known broad spectral properties of bomb blasts (Woodman *et al.* 2003, Braulik *et al.* 2017, Cagua *et al.* 2014). This was set to run at a very high false positive rate and low false negative rate i.e. it detected the majority of bomb blasts but also a lot of other sounds. Acoustic visualisation software was then developed to allow a manual analyst to efficiently verify the automated detections and extract the bomb blasts.

Blast detection

After every deployment the acoustic data was decompressed using the SoundTrap host software and then processed in the open source software PAMGuard (www.pamguard.org). The PAMGuard implementation of the Ishmael Energy sum detector [www.bioacoustics.us/ishmael] was used to extract any received sounds for which the spectral energy between 750 and 2250Hz passed a threshold for a minimum time period (130 ms). Initially this was set as a static threshold however high levels of shipping noise near Dar es Salaam caused the detector to continuously trigger, generating an unmanageable number of false detections. The algorithm was therefore modified to implement an adaptive threshold. The spectral energy noise floor was tracked using a weighted cumulative moving average window. A detection was triggered only if the energy was above the moving average window plus the threshold value (Figure 4). Thus, during ship noise the sensitivity of the detector was effectively reduced, minimising the number of false detections and allowing for manageable data quantities. Ishmael detector settings are in Annex B.

Blast classification

Ishmael detections were saved as ~3 second wav clips using the PAMGuard clip generator module. A manual analyst could determine whether a clip was a bomb blast by listening to it. However, on average there were 10,000 clips per 3 month deployment. Listening to every clip was laborious and would have taken several months, consuming all of the available analysis time. To speed up the process SoundSort software was created to visualise all clips during a deployment. Spectrograms of each clip were displayed as a gridded mosaic which could be easily viewed, panned and zoomed by the program user (Figure 5). Bombs represented on a spectrogram (see Figure 6) are distinguishable as multi-modal transient-like sounds. An analyst used SoundSort to visually check any spectrograms that appeared to be bombs, and then clicked on the clip to listen to it to confirm that it was a bomb. This greatly sped up analysis of the datasets allowing an analyst to manually extract bomb blasts from a 3 month deployment in around 2-3 hours.

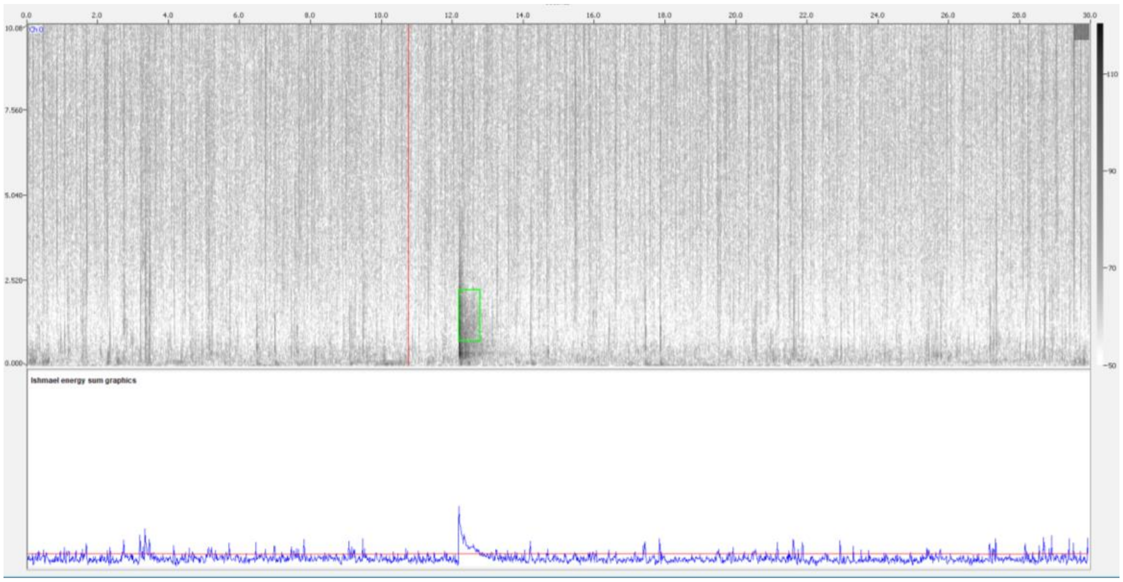
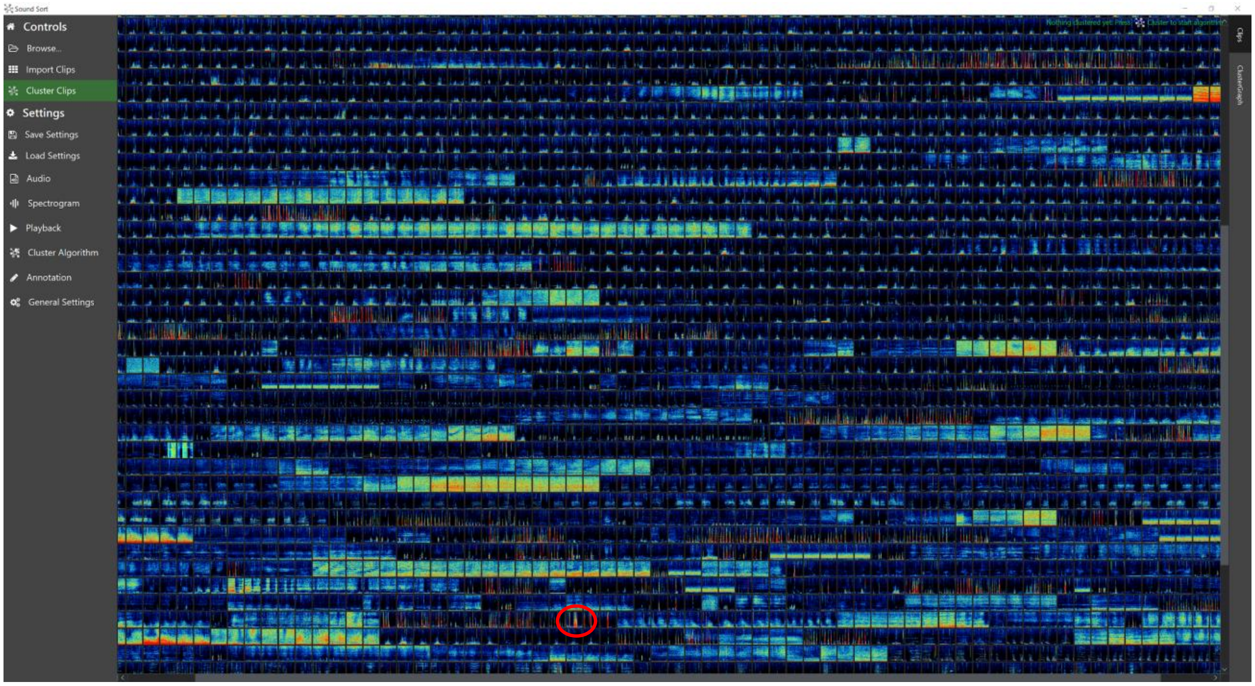


Figure 4 - Ishmael detector analysing spectrogram data. The fish bomb blast is located 12 seconds into the spectrogram window. The bottom panel shows the spectral energy time series and the red line is the current threshold level. Note that there are often brief transients which pass above the threshold however the majority of these were discarded by defining a minimum time over the threshold parameter.



Nothing clustered yet. Press Cluster to start algorithm

Figure 5. An example of all detected clips from a single deployment. There are a large number of false positive detections which is a consequence of using a relatively simple detection algorithm in a complex soundscape. Sounds that triggered false positives included ship noise, fish vocalisations, humpback whales, dolphin whistles and many other unknown sound types. Many of these are easily identifiable by glancing at the spectrogram and thus a manual analyst can quickly use SoundSort to navigate to bomb-like sounds. A bomb is circled in red.

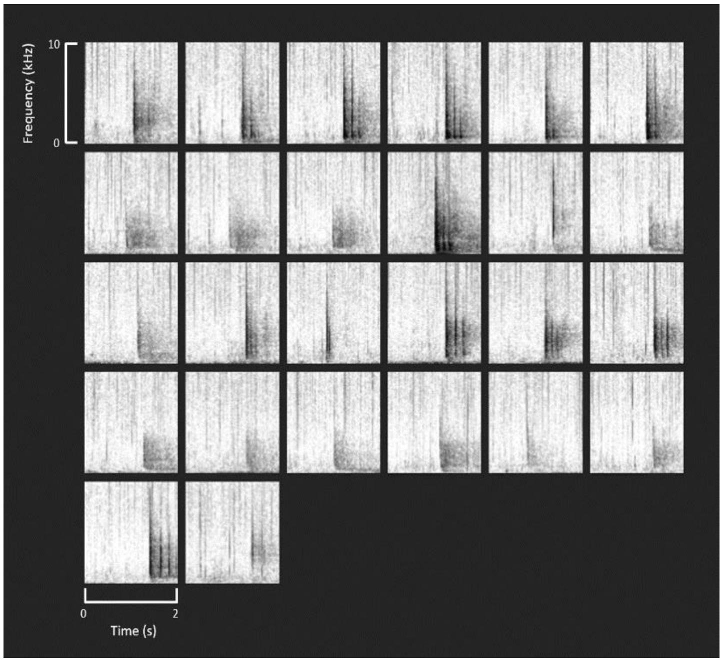


Figure 6 - All bomb blast clips from a single deployment near Maziwe Island represented on a spectrogram in [SoundSort](). Bomb blasts are recognisable on a spectrogram by a sharp onset and, at higher received levels, a distinct multi modal structure likely caused by multi-path propagation (i.e there is the initial blast followed by numerous echoes). Varying absorption rates at different frequencies means that the received spectral characteristics vary significantly depending on the bomb range which makes automated classification more challenging.

Blast Localisation

Manually verified bomb blasts were exported to MATLAB (Mathworks) and a custom script used to localise the bearings to each blast. The clips were bandpass filtered between 750Hz and 10000Hz. The filtered data was then cross correlated to calculate the time delays between the bomb blast at each of the three different hydrophones on each recording station. The time delays were passed to a simplex minimisation algorithm (Lagarias *et al.* 1998) which calculated the bearing to the blast. Bomb blasts are relatively broadband transient sounds which resulted in well-defined peaks in the cross-correlation function (see Figure 7) and therefore accurate time delay measurements and bearings.

Meta Analysis

Blasts were assigned to tidal state, with any occurring within 1 ½ hours of low or high tide assigned as low or high, and blasts in between as either rising or falling tide. Spring tides were those on, and up to three days after, the full or new moon, while neap tides were assigned to three days that occurred 7, 8 and 9 days after the spring tides. All others days were assigned as normal tides. Archived modelled forecast wind speed data, available at two hourly intervals during the monitoring period, was downloaded from Windguru (www.windguru.cz) for the station on north Zanzibar, Ras Nungwi. These are modelled wind forecasts not measured wind speeds, and thus provide a broad indication of general weather at the time but are not an exact reflection of sea conditions above the recorder. Patterns in blasting occurrences were explored according to month, day, time of day, wind speed, tidal state and phase of the moon. A Generalised Linear Model (GLM) implemented in RStudio (Version 1.3.959) was conducted to explore which environmental factors influenced blast fishing activity.

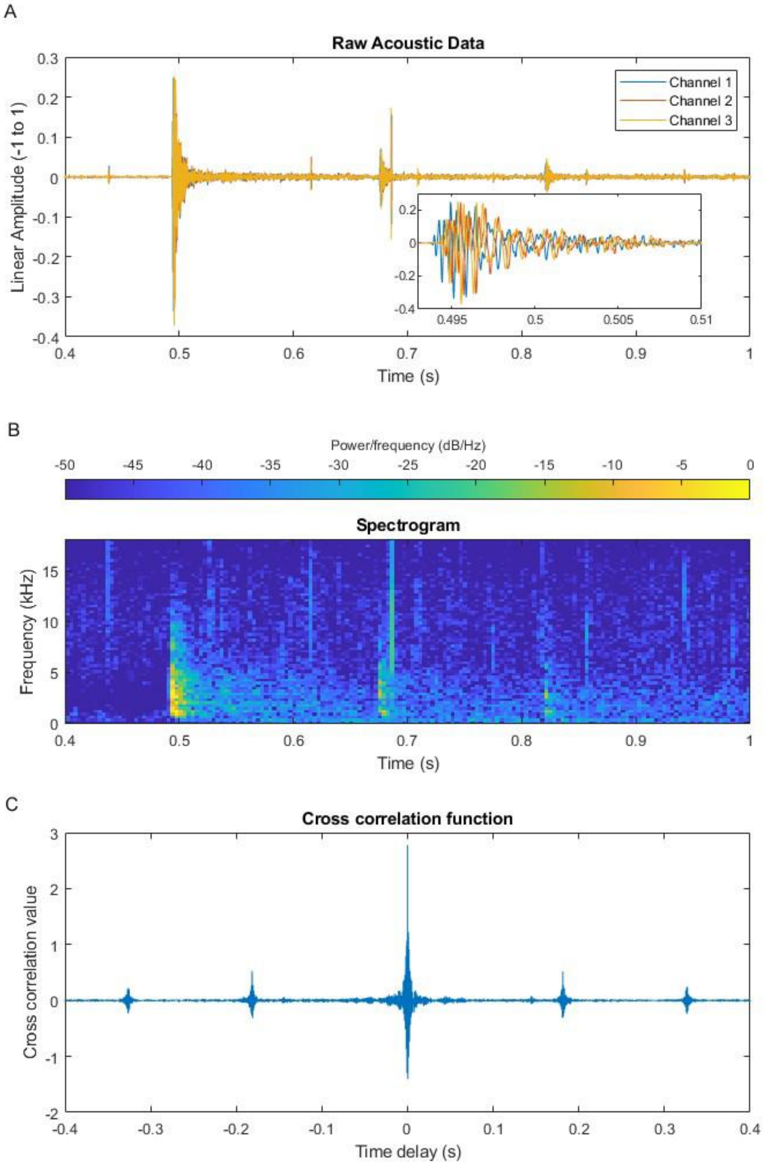


Figure 7. An example of a bomb blast and time delay measurement. The top plot (A) shows the raw waveform of a bomb blast. The initial direct path blast occurs at ~0.5 seconds and distinct echoes are then received at 0.68 and 0.82 seconds. The top subplot (A) shows the initial direct path bomb blast in detail. The middle plot (B) is the corresponding spectrogram of the bomb blast which shows that it is relatively broadband (between ~0.01 and ~10kHz). The lower plot (C) is the cross-correlation function of two channels - the multiple peaks are caused by echoes, however, these are outside the possible array bounds and can be ignored. The maximum of the central peak, which corresponds to the correct time delay measurement, is very distinct and thus time delay measurements (and therefore bearing measurements) are likely to be accurate.

Results

Deployment

Acoustic recording stations were deployed at the end of May and the beginning of June 2018. Initially three stations were deployed, two near Dar es Salaam (Location 1. Mbudya Banks and Location 3. Dar Anchorage on Figure 1) and a third near Pangani in Tanga region (Location 2. Maziwe on Figure 2). A fourth unit was deployed in August 2018 in Tanga near to Moa (Location 4. Fish Eagle). Location 3 was close to the ship anchorage in Dar es Salaam and analysis of the first deployment data showed that background noise from the ship engines and generators was too loud to be able to detect bombs; this site was discontinued in mid-October 2018 and a new location for deployment chosen near the island of Zanzibar (Location 5. Bedford Banks). The arrangement of recording stations at the Dar es Salaam site allowed for the triangulation of the exact location of blasts as they could be detected simultaneously on both units. However, the configuration of the coastline in Tanga, which has extensive shallow reef and island systems parallel to the coast, meant that it was not possible to deploy two units in a configuration that would allow blasts to be detected simultaneously, therefore in Tanga it was only possible to obtain the bearing to the origin of the blast and not exact locations.

In January 2019, two of the five recording units malfunctioned due to internal water seepage and consequently the number of recording stations was reduced to three. Recording at Location 5 Bedford Banks was discontinued from that point forward. Deployment time, duration and detected blasts are illustrated in Figure 8 below.

Patterns in Blast Fishing Activity

A total of 54 blasts (on a 50% duty cycle) were detected, and 108 blasts estimated, during 695 acoustic recording days between June 2018 and May 2019. A total of 49 blasts were recorded, and 98 blasts estimated to have occurred in Tanga, during the 279 days of recording. By contrast off the coast of Dar es Salaam only 5 blasts were recorded, giving an estimate of 10 blasts that occurred, during 416 days of recordings over the same time period (Table 1, Figure 8). The location with by far the largest number of blasts detected was around Pangani (Location 2), where 80 blasts, representing 74% of the total, were estimated to have occurred during the 169 day (approximately 5 ½ months) recording period (Figure 9, Table 1). Fifty of the 80 estimated blasts occurred during the first deployment, in June and early July 2018 when there were still several blasts per day. Fewer blasts were detected at this site later in the year, however, a small number were still being detected by the final deployment in May 2019 suggesting that blast fishing continues in the area north of Pangani town, towards Tanga. The number of bombs detected, standardised by the number of hours of recording, was highest in June, July and September 2018, and was low in August and October 2018 and for January to May 2019 (Figure 10).

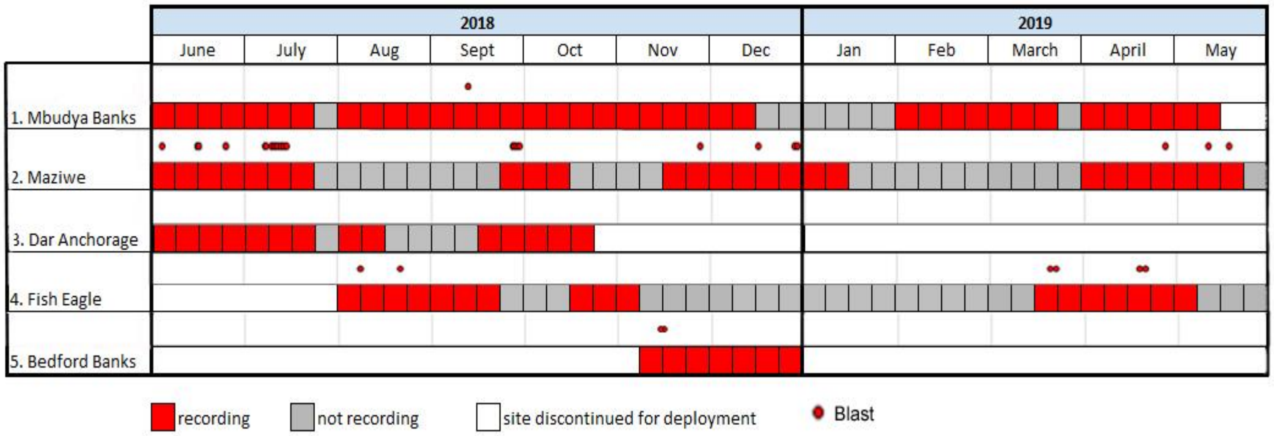


Figure 8 - Deployment and data recording timeline of the five blast fishing recording stations off the coast of Northern Tanzania from June 2018 to May 2019 (see Figure 2 for deployment locations).

Table 1 - Deployment duration and blasts detected at each acoustic recording station on the Tanzanian coast.

Location #	Location Name	Region	Number of Deployments	Days of Recordings	Number of Blasts on 50% duty cycle	Estimated actual number of blasts	Blasts / day*
1	Mbudya Banks	Dar es Salaam	6	274	3	6	0.02
2	Maziwe	Tanga	3	169	40	80	0.47
3	Dar Anchorage	Dar es Salaam	3	92	0	0	0
4	Fish Eagle	Tanga	3	110	9	18	0.16
5	Bedford Banks	Dar es Salaam	1	50	2	4	0.08
	Total	-	16	695	54	108	-

*one day defined as 12 hours of daylight as blasting was never recorded at night.

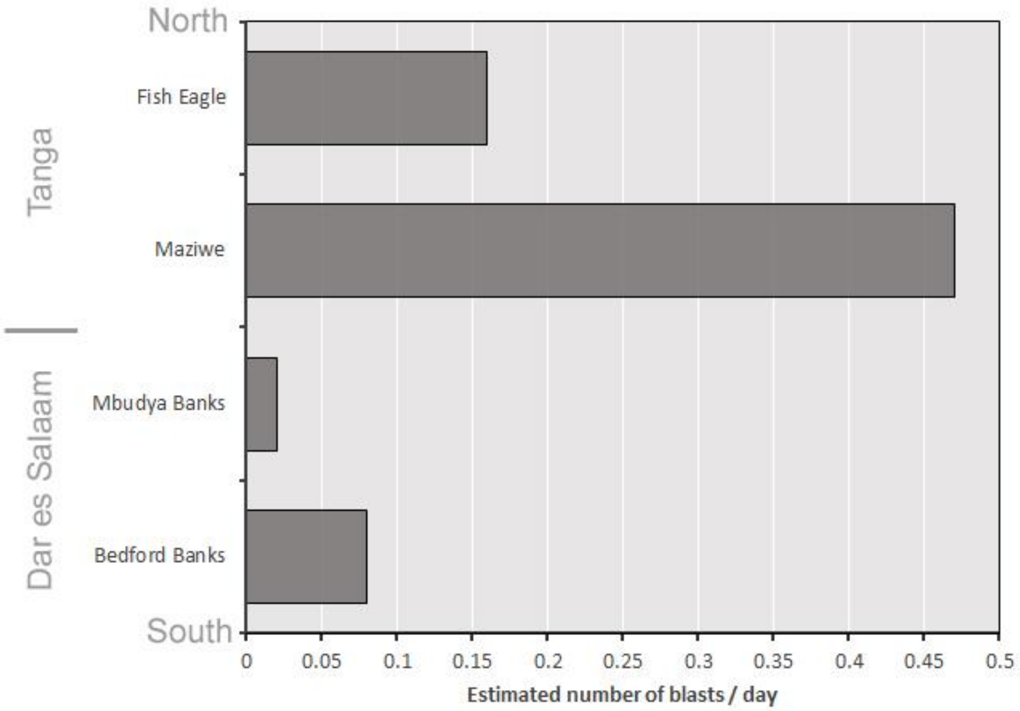
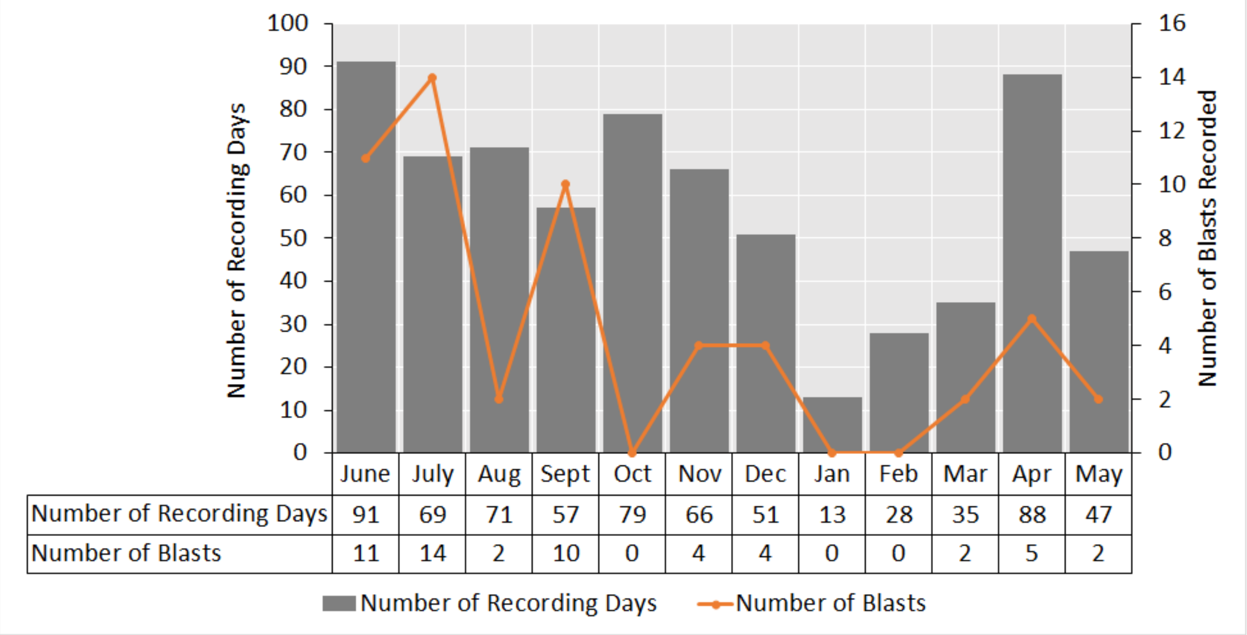


Figure 9 – Estimated number of blasts / recording day at each of four locations (see Figure 2) along the Tanzanian coast, with sites in the north of the country at the top of the graph and those in the south at the bottom.



	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Number of Recording Days	91	69	71	57	79	66	51	13	28	35	88	47
Number of Blasts	11	14	2	10	0	4	4	0	0	2	5	2

Figure 10 - Recording hours and number of blast fishing explosions (on a 50% duty cycle) detected per month.

Blast fishing explosions were recorded at similar levels throughout the week and weekend with no clear preference for any day of the week. The slightly larger number of blasts detected on Saturday compared to other days was because on Saturday 16th June 2018 between 8:30 and 11:30am, 8 blasts were detected at Maziwe making that the single day with the largest number of blasts detected during the entire study (Figure 11).

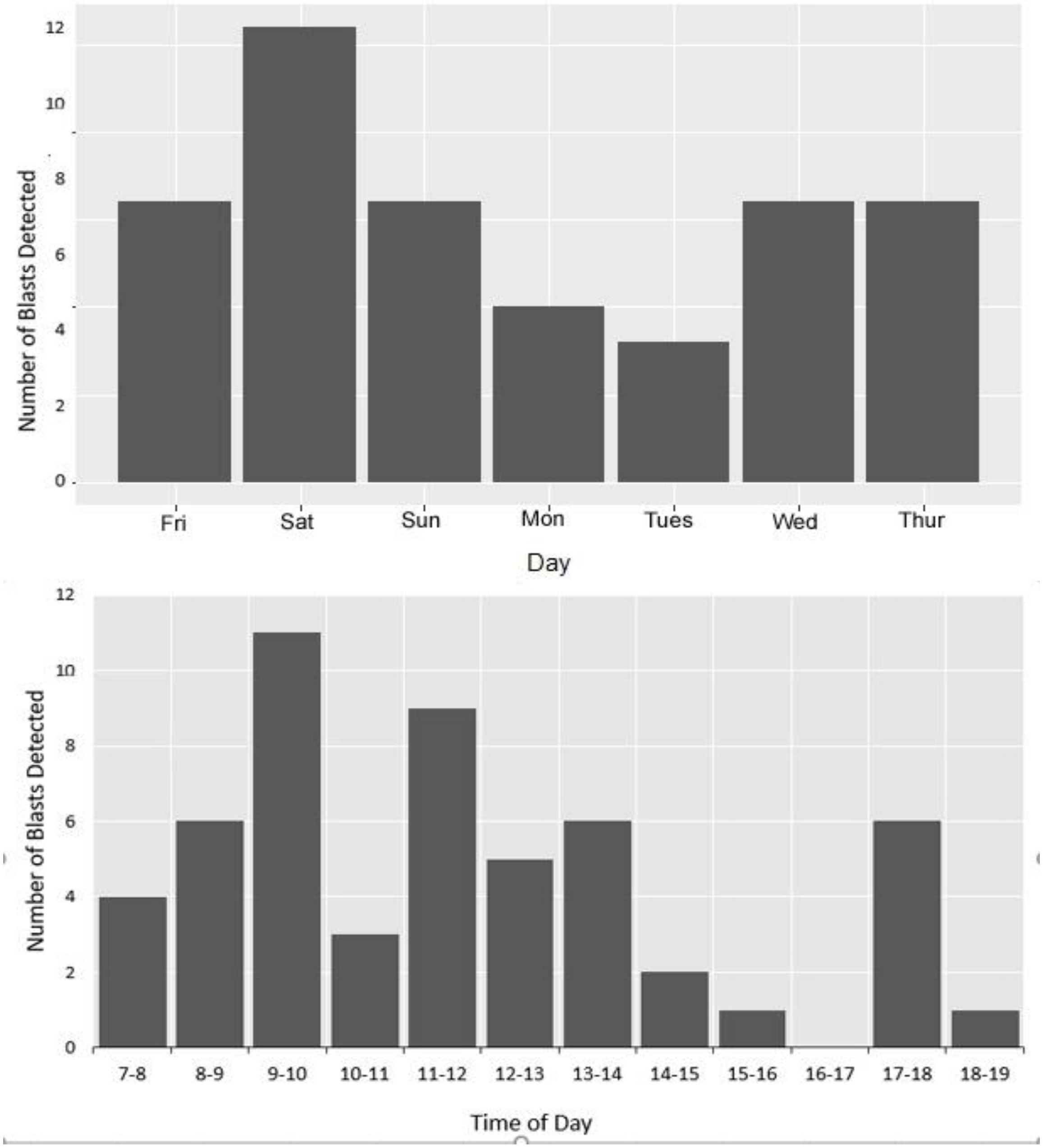


Figure 11 - Number of blasts detected by day of the week and time of the day

When the data were disaggregated by site (see Annex C) there is a suggestion that in the Tanga area blasting incidence is higher towards the end of the week, on Friday, Saturday and Sunday, compared to the beginning of the week, but there is insufficient data to test whether this is significantly so.

As with previous studies the majority of blast fishing activity occurred during the morning hours between 7am and 2pm. A total of 40 blasts, almost three quarters (74%) of the total, occurred in the six hours between 8am and 2pm (Figure 11, Annex C). Blast fishing occurred predominantly during low and falling tides (65% of detected blasts, n=35), with only 35% (n=19) occurring during high and rising tidal states (Table 2). Although the data is limited, there are indications that blasts detected during high and rising tide were generally further off shore than those detected during low and falling tide. More than half (53.5%, n=29) of all blasts detected occurred during spring tides (Table 3), and by contrast blasting rates were very low during neap tides (5.6%, n=3). The majority of detected blasts (67%, n=36) occurred during windy conditions of 20+ kph.

Table 2 - Number of blasts detected according to tidal state

Tidal State	Number of Blasts	%
Falling	16	29.6
Low	19	35.2
Rising	9	16.7
High	10	18.5
	54	**100%**

Table 3 - Number of blasts detected according to moon-cycle

Moon cycle	Number of Blasts	%
Spring	29	53.7
Mid-moon cycle	22	40.7
Neap	3	5.6
	54	**100%**

For each day during the one-year monitoring period, the number of detected blasts, the wind speed (kph) at 9am, the tidal phase (Spring, Neap, or Normal tide) and date were assigned. The predictor variable in a Generalised Linear Model was the number of detected blasts, and the explanatory variables were wind speed, tidal phase, and date. The final model with lowest AIC retained spring tides (est: 1.131706, St Dev. 0.484632, z=2.335 p<0.05) and date (est: -0.006063, St Dev. 0.001461, z=-4.149, p<0.001) as the most significant explanatory variables. Blast fishing was significantly more likely to be detected during spring tides than at any other time of the lunar/tidal cycle. Blasting activity was greatest early in the monitoring period and it declined throughout the study. There was no effect of wind on explosion detections.

The bearing to each detected blast was determined based on time of arrival differences at each hydrophone. There were no blasts either in Tanga or Dar es Salaam that were detected simultaneously at two locations and therefore it was not possible to triangulate the exact location of any blast. The bearing to each blast is depicted on Figure 12; at location 4 in the north, near Fish Eagle most blasts came from the north or east of the recorder towards the Kenya border area. Several of these blasts were extremely loud and clearly occurred within a few hundred meters of the recording station. At location 3, near Pangani town most blasts occurred to the north of the recorder on the outer edge of the offshore banks in the southern part of Tanga Coelacanth Marine Park. At locations 2 and 5 off Dar es Salaam very few blasts were detected and there was no clear pattern regarding blast location.

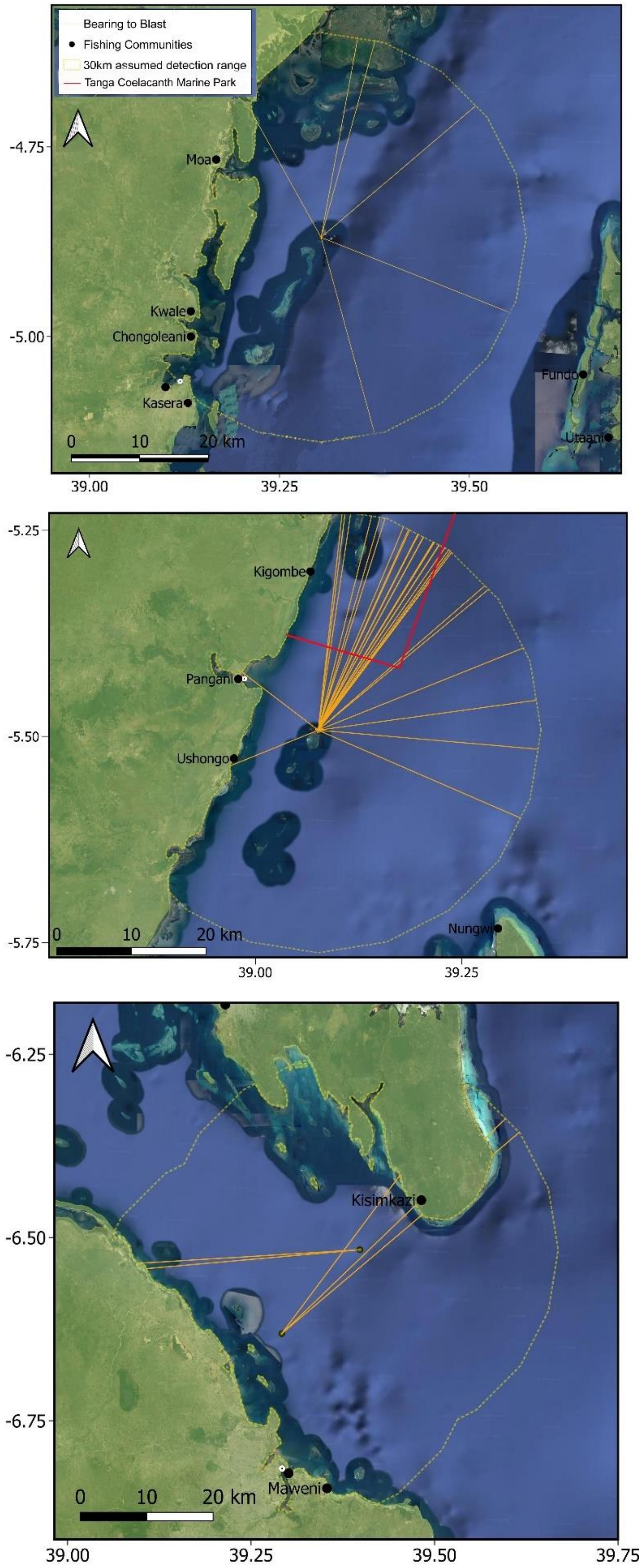


Figure 12 - Bearing from acoustic recording stations to detected blasts (top) Fish Eagle, (middle) Pangani, and (bottom) Dar es Salaam. Bearing lines are truncated at 30km, the approximate maximum detection distance. Blast could have occurred anywhere along the bearing line.

Discussion

Blast Detection Methodology

Extracting the sound of bomb blasts with confidence from large amounts of acoustic data especially from areas with broadly unknown soundscapes requires development of computer algorithms that can detect blasts with an acceptable error rate. Here a hybrid analytical approach was used involving relatively simplistic automated detectors that extracted any sounds of interest and then powerful data visualisation tools to allow manual analysts to explore the results and extract bomb blasts. Once the algorithms and detectors had been developed and refined, this approach was very efficient, requiring less than a day of expert analysis time per deployment. Now that the analytical tools are in place, expert analysis time of future acoustic monitoring deployments is likely to be fairly short and not too technical thereby making it a cost-effective and affordable way of monitoring blast-fishing and reducing the analytical time post deployment.

This work would have been strengthened if we had been able to ground-truth the data and obtain visible or audible confirmation that the noises identified were indeed bombs. However, blast-fishing was sufficiently rare during the study period that it was not possible to do this, but the acoustic signature of explosions is distinctive and unequivocal. Despite the minimal time required to analyse each deployment, a manual analyst still requires some training and can be relatively expensive to employ. This methodology would therefore benefit from more accurate automated analysis algorithms (i.e. algorithms which detect the majority of bomb blasts with very few false positives). This would both negate the need for expert analysis time, allow the current acoustic monitoring for bomb blasts to continue on a more restricted budget and would mean that the monitoring program could eventually be scaled up to include more devices without incurring significantly increased analysis costs. However, developing such algorithms is not straightforward. An automated algorithm with sufficient accuracy is almost certainly going to be based on machine learning (likely deep learning) and thus require significant training datasets. The limited bombs detected in this survey likely will not suffice to train a new classifier, however, there are other datasets that could be used (e.g. Braulik *et al.* 2017), and there may be potential to use transfer learning and data augmentation to develop efficient classifiers (e.g. Ibrahim *et al.* 2020, Zhong *et al.* 2020). This should be the focus of further research into analytical methods.

It was not possible to determine the exact location of blasts using triangulation between two recording units as was originally envisaged, largely because almost no blasts were detected in the Dar es Salaam area which was the only place where the recording stations were able to be suitably configured to allow for triangulation. Locating the exact position of explosions using triangulation is still a technical possibility for future studies and will be more easily accomplished if blasting levels increase. Care needs to be taken to ensure that where units are deployed on a 50% duty cycle that they are both recording at the same time so that it is possible to detect a blast on both units simultaneously. This also becomes challenging where, as occasionally happens, units suffer intermittent power issues that change the timing of the duty cycle such that initially time synched units shift out of synchronisation during their deployment. However, despite these challenges, the knowledge that is gained by being able to identify with certainty the exact location where blast fishing is occurring is extremely important for enforcement and it is desirable to continue deployment of units in suitable configurations such that this is attainable.

Blast-fishing Practices and Patterns

One of the striking patterns in blast-fishing activity documented in this study was that in Tanga it was conducted predominantly at low tide, largely during spring low tides. This may in part be because the nearshore marine environment is already substantially degraded and by waiting for low spring tides fishers are able to access deeper, less heavily fished habitats further offshore, thereby maximising their yields. The significance of low tides for blast-fishing more generally is that it is easier to retrieve blasted fish during low spring tides since rupturing of fish swim bladders causes most blasted fish to sink. Sea conditions are also generally calmer during low spring tides.

The fact that the majority of blast-fishing occurs during the morning on any day of the week has been found during all other blast-fishing studies in Tanzania (Mwambao Coastal Community Network 2016, Cagua *et al.* 2014, Braulik *et al.* 2017, Tanzania Blast Monitoring Network, 2020). It was assumed in the past that blasting in the morning was partly to avoid windy conditions which are more prevalent in the afternoons, however we did not find any significant effects of wind speed on the number of blasts recorded. Both the data from this study, and that gathered by the Tanzania Blast Monitoring Network's land-based recorders, logged many blasts during the windiest months of the year, June, July and August, and therefore it is assumed that either high winds to not impede fishers from blast-fishing, or, there are sufficient sheltered spots behind islands and reefs that allow blasting to continue even in adverse weather.

The largest amount of continuous recording effort during this study was off the coast of Dar es Salaam but almost no blasts were detected in this area. During a towed acoustics study in 2015, 123 blasts, 38.7% of all those detected along the entire coast, were within 50 km of Dar es Salaam, and 196 blasts, which is 61.6% of the total, were within 80 km of the city which was clearly one of the national hotspots of blasting activity at that time (Braulik *et al*. 2017). Similarly, in data collected by the Tanzania Blast-Monitoring Network from May to December 2016, blasts recorded at 7 locations within 50km of Dar es Salaam constituted 22% of the total number of blasts from all 24 locations along the coast. The lack of blasts detected around Dar es Salaam during this 2018-2019 study confirms that enforcement activities by authorities during 2017-2018 have been effective in eliminating blast-fishing around Dar.

In the Tanga region we documented that blast-fishing continues, albeit at levels much lower than in years prior to 2017. The area of highest prevalence appears to be the offshore reefs in Tanga Coelacanth Marine Park. A small number of (6) blasts were also detected further north off the coast of Mkinga District. The widely varying bearings of these blasts may mean that blasting was conducted in offshore areas, but it is more likely that they were in fact very close to the recorder on the reef. By blasting on the seaward side of the offshore reef complexes that are approximately 20km from shore, the noise of the explosions are unlikely to be heard by anyone on land. In this way, blast fishers can continue their activities with little fear of detection. The frequency and pattern of blasts detected in Tanga during this study suggest that there are likely to be only a small number of fishing vessels responsible for the residual blast-fishing effort in Tanga Region during the period June 2018 and May 2019, possibly as few as two[1]. Based on the data from this study, one vessel appears to have been operating within, and offshore from, the outer reefs in Tanga Coelacanth Marine Park. Another appears to have been operating predominantly in offshore waters off the northern Mkinga District coast. One appears to be operating within, and offshore from, the outer reefs in Tanga Coelacanth Marine Park. The other appears to be operating predominantly in offshore waters off the northern Mkinga District coast. However, it is important to note that our recorders likely did not monitor the waters in the vicinity of Tanga town

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[1] Pers. comms. District Fisheries Officer, Tanga and Warden-in-Charge, Tanga Coelacanth Marine Park

and that it is possible that there is also blasting in that area that was out of the detection range of our equipment.

Comparison of Land-based and Acoustic Methods

There were seven months (June to Dec 2018) where land-based monitoring and acoustic monitoring occurred concurrently. Both methods recorded small numbers of blasts at the beginning of that period in June and July 2018, but what is notable is that between September and December 2018 the land-based recorders did not document a single blast, while the acoustic recorders picked up 18 explosions. The acoustic units were able to pick up more blasts than land-based monitors, and recorded blasts when the land-based recorders did not. It is likely that in the face of increased surveillance and enforcement efforts by the government, blast-fishers stopped blasting closer to shore where land-based recorders could hear the blasts, but continued in more remote locations where only the acoustic recorders were able to detect them. This demonstrates the advantage of using acoustics to document blast-fishing activity. The location of the underwater units are unknown and essentially undetectable to fishers; so they cannot intentionally avoid them, and strategically located acoustic units can monitor large remote areas of the ocean as well as more accessible coastal areas. The two methods are similar and given the big difference in the area that is monitored the results they generate are different and not directly comparable although both will be able to demonstrate trends in blasting over time.

Trends in Blast Fishing Occurrence

The data collected in this study support and corroborate the separate conclusions of the TBMN land-based recording network and of Tanzanian government authorities, that blast fishing has declined dramatically since 2016-7 and is at what is very likely to be the lowest levels for the 4-5 decades in Tanzania. Figure 13 overlays the blast-fishing occurrence data recorded by land-based monitors at 24 sites along the coast of Tanzania from May 2016 (Tanzania Blast Monitoring Network, 2020), with the blasts recorded on the five acoustic recorders deployed from May 2018 onwards in the current study. The two datasets are not directly comparable because the two methods are surveying mostly different locations, times, and areas of the ocean, however both datasets reinforce that there has been a dramatic reduction in the occurrence of blast fishing since 2016 and that this reduction continued until May 2019 when acoustic recording stopped.

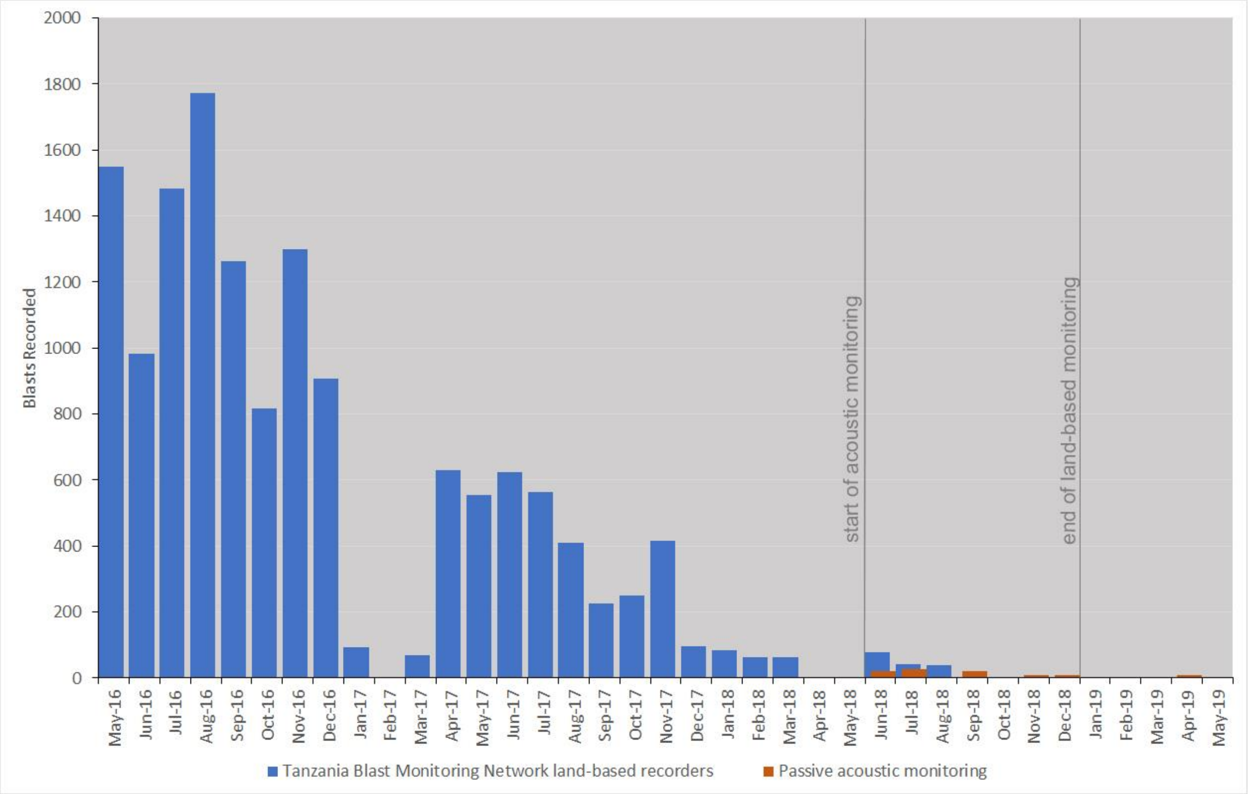

Figure 13 - Data on the number of blasts recorded by land-based recorders in the Tanzania Blast Monitoring Network (2020) during 2016-18, and the acoustic recorders deployed in this study during 2018-19. [Note: TBMN data is not directly comparable with the acoustic data in terms of spatial coverage, however they are displayed on the same graph to illustrate overlapping timing of the two studies and overall, broadly compatible trends].

Based on this study, it is concluded that although blast-fishing has dramatically reduced along the Tanzanian coast it has not been completely eliminated. It is recommended that, for maximum effectiveness, enforcement agencies focus effort on identifying and intercepting the vessels operating along offshore reefs in the above-mentioned areas of Tanga Region, during morning hours, especially during spring low tides.

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Annex A - Detected Blasts

Maziwe Recorder

Date & Time
6/4/2018 12:29:53
6/16/2018 8:29:45
6/16/2018 9:22:11
6/16/2018 9:23:03
6/16/2018 9:24:45
6/16/2018 9:29:57
6/16/2018 11:08:16
6/16/2018 11:13:16
6/16/2018 11:27:47
6/25/2018 8:15:53
6/25/2018 9:06:39
7/8/2018 9:34:31
7/8/2018 12:52:37
7/10/2018 9:31:09
7/10/2018 9:31:31
7/11/2018 7:59:01
7/11/2018 8:40:15
7/11/2018 8:40:34
7/12/2018 7:40:49
7/12/2018 8:40:25
7/13/2018 9:30:39
7/13/2018 9:48:03
7/13/2018 9:50:32
7/14/2018 12:32:11
7/15/2018 8:41:02
9/27/2018 13:20:17
9/27/2018 13:20:33
9/27/2018 13:20:44
9/27/2018 17:41:58
9/27/2018 17:43:42
9/28/2018 18:02:44
9/29/2018 12:35:18
11/27/2018 11:57:31
12/16/2018 12:37:07
12/28/2018 10:44:00
12/28/2018 11:45:00
12/29/2018 13:33:24
4/28/2019 14:57:29
5/12/2019 17:38:01
5/19/2019 11:27:12

Fish Eagle Recorder

Date & Time
8/8/2018 14:29:37
8/21/2018 15:20:55
11/2/2018 11:33:51
03/22/2019 7:29:58
03/24/2019 7:00:27
4/20/2019 10:07:07
4/20/2019 10:10:08
04/22/2019 13:12:39
04/22/2019 13:16:42

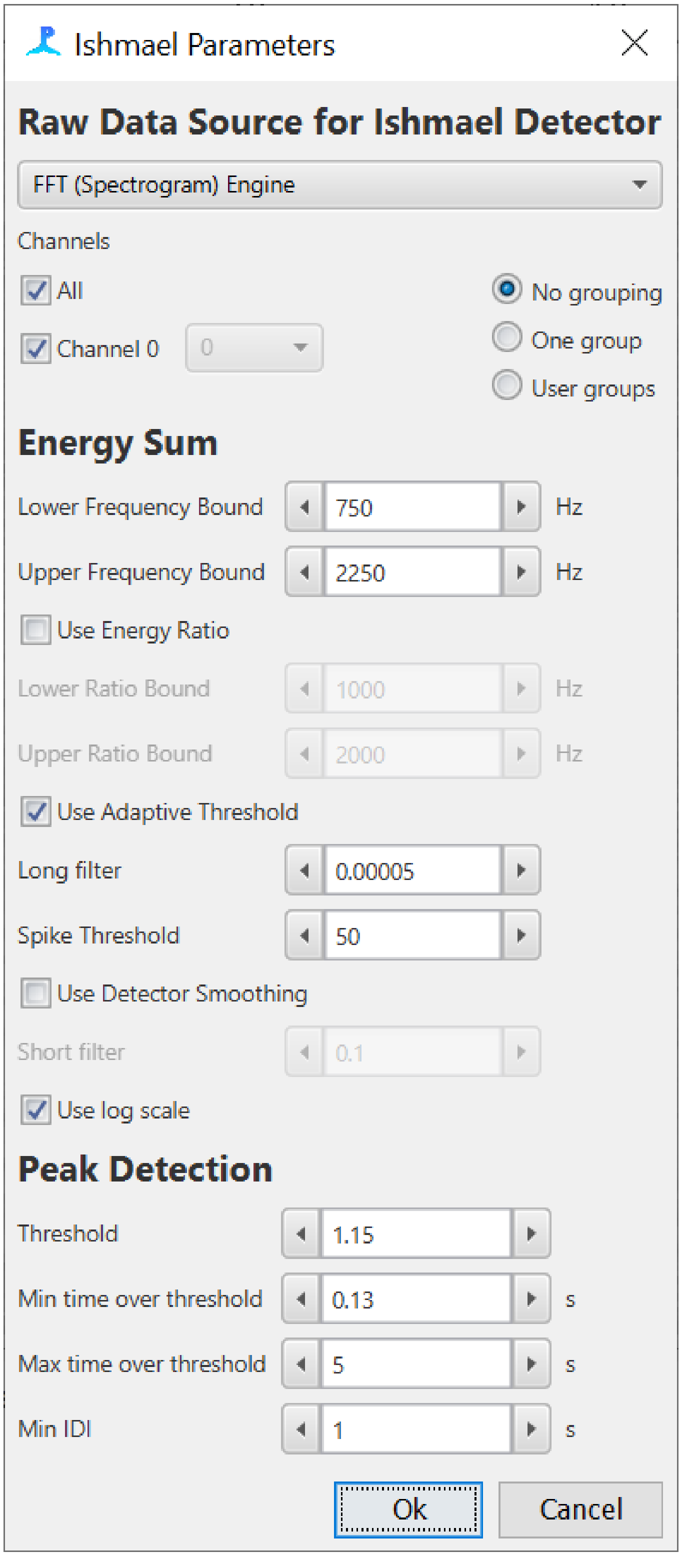
Mbudya Banks

Date & Time
9/12/2018 17:14:22
9/12/2018 17:15:51
9/12/2018 17:16:31

Bedford Banks

Date & Time
11/14/2018 11:33:53
11/15/2018 11:54:54

Annex B - Ishmael Energy Sum Detector Settings



Ishmael Parameters

Raw Data Source for Ishmael Detector

FFT (Spectrogram) Engine

Channels

☑ All

☑ Channel 0 — 0

● No grouping

○ One group

○ User groups

Energy Sum

Lower Frequency Bound: 750 Hz

Upper Frequency Bound: 2250 Hz

☐ Use Energy Ratio

Lower Ratio Bound: 1000 Hz

Upper Ratio Bound: 2000 Hz

☑ Use Adaptive Threshold

Long filter: 0.00005

Spike Threshold: 50

☐ Use Detector Smoothing

Short filter: 0.1

☑ Use log scale

Peak Detection

Threshold: 1.15

Min time over threshold: 0.13 s

Max time over threshold: 5 s

Min IDI: 1 s

Annex C – Detected Blasts at the two Tanga recording locations broken down by Day of the Week and Time of the Day

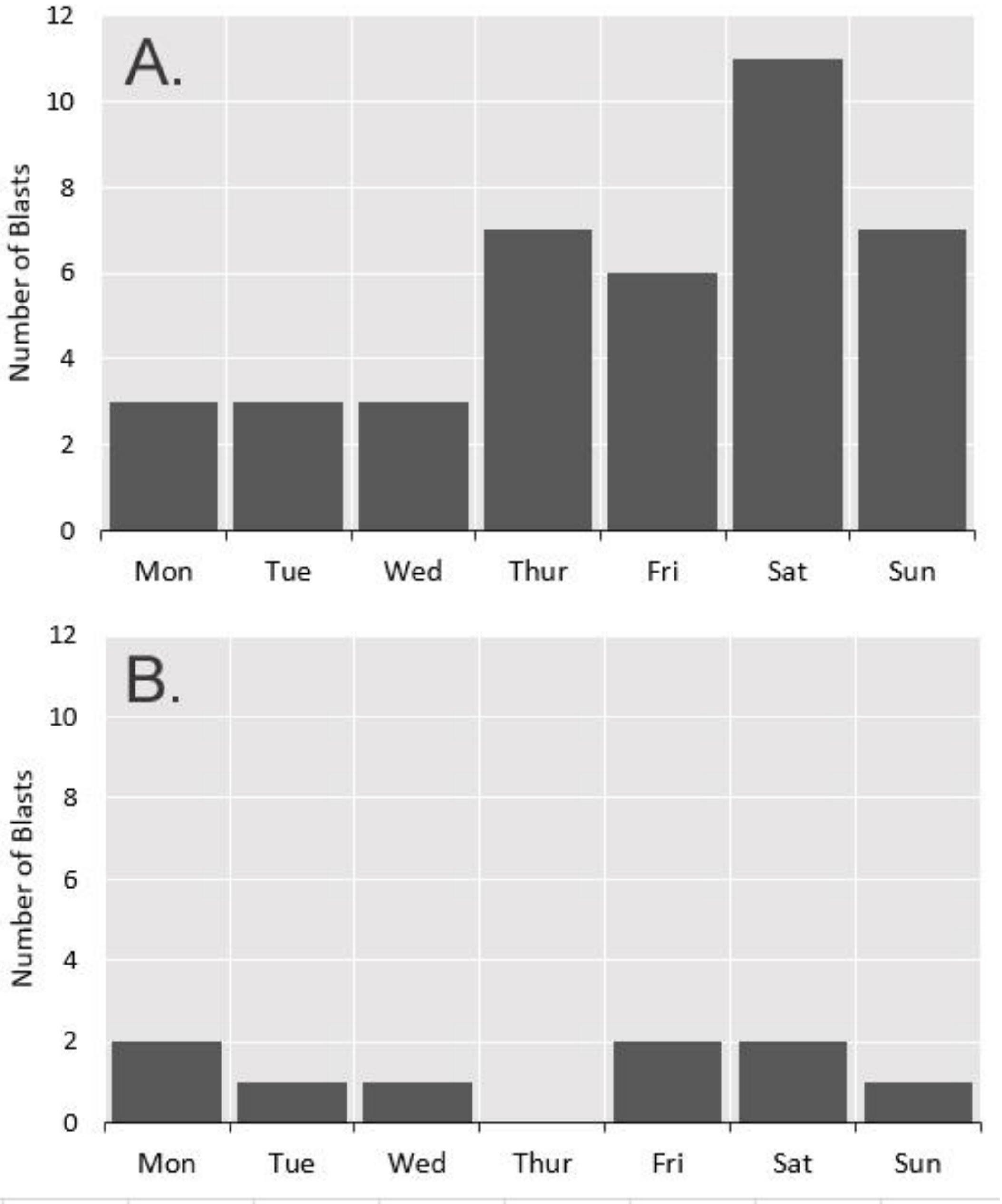


Figure A1 – Number of blasts detected according to the day of the week at A. Maziwe, and B. Fish Eagle recording stations

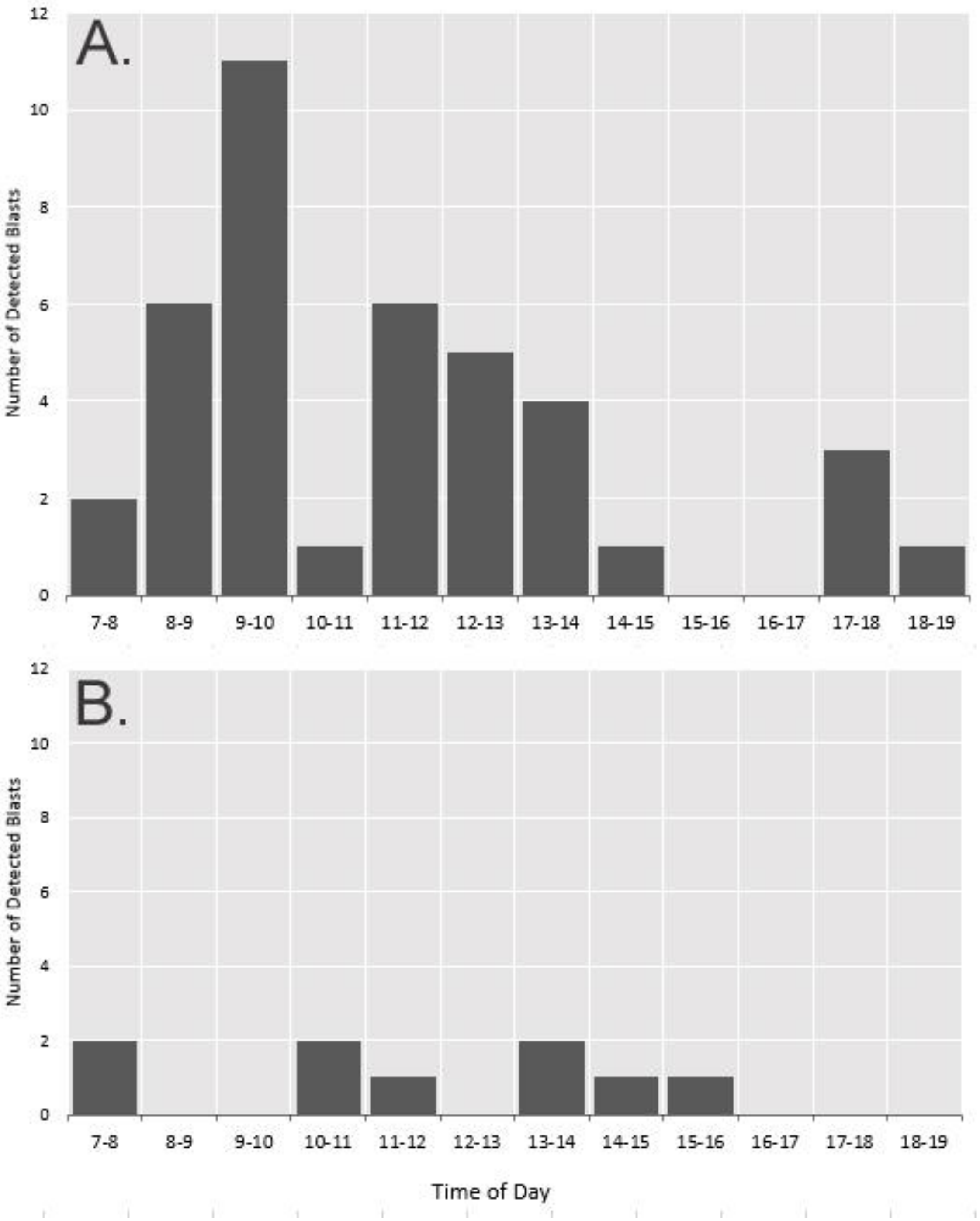


Figure A2 – Blasts detected at A. Maziwe and B. Fish Eagle in Tanga broken down by time of day