IMFACT - Integrated Monitoring of Fish Abundance using Combined Tools

Project Report

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Executive Summary

Visual census is a commonly used method for monitoring fish abundance in Marine Protected Areas (MPAs) and coastal seas. Its reliance on human vision and on scuba diving however presents many limitations and biases. The IMFACT project proposes to complement common visual census applications with an integrated toolbox composed of a Remotely Operated Vehicle (ROV) and a hydroacoustic system, to advance monitoring of fish abundance and diversity in coastal areas and MPAs. The integrated approach we propose should ideally complement traditional diving-based visual census, providing a holistic picture (covering areas, species and mechanisms under-surveyed by visual census) and more accurate estimates of fish abundance (accounting for observation bias intrinsic in visual census). The project scoped three objectives: 1) Identify and quantify bias in visual census (e.g. fish escape response triggered by visual census operated by a snorkeler) through ground-truthing using the hydroacoustic array. 2) Explore the feasibility of a) monitoring fish in deeper coastal waters (ca. 30-80 m) with both tools, extending to previously under-monitored areas, while reducing the risk for operators; b) utilizing the hydroacoustic array to monitor pelagic fish in the water column and c) monitoring fish inshore-offshore nightly migrations; 3) develop a protocol for integrated monitoring based on the results.

The project objectives were fully explored and, to a major extent, reached. It was, for example, possible to identify biases caused by the alternative sampling methods: while the quantification of bias was not as straightforward, the project pinpointed alternative approaches suitable for such quantification. The combined toolbox was indeed effective in monitoring fish acoustically and visually at various depths, and in detecting mobile species including small and large demersal and pelagic fish, which are key resources for small-scale fisheries and for tourism.

While caveats and limits have been identified, it emerges clearly that the proposed approach may be highly suitable for monitoring fish abundance, biomass and behaviour in coastal demersal and pelagic areas. Our toolbox could thus enable MPA managers and scientists to improve accuracy in the estimation of fish abundance and biodiversity, ultimately facilitating sustainable fisheries management and contributing to MPAs conservation goals.

The project relied on close interaction with local partners and stakeholders in the selected study area, the Caribbean island of Bonaire (The Netherlands). Through a close collaboration with STINAPA, the agency in charge of the MPA management and enforcement in Bonaire MPA, key aspects of interest for multiple stakeholders were identified. These included monitoring of habitats and species of conservation and commercial interest, conflict resolution, effectiveness of spatial closures for various user groups including small scale fishers, tourism operators, and environmental NGOs. The project also confirmed the suitability of Bonaire as an interesting research area suitable for testing tools and approaches and highly interesting for further studies in this field.

Contents

Introduction

Visual census is a common method used to monitor fish abundance in Marine Protected Areas (MPA) and coastal seas. Its reliance on human vision and on scuba diving however presents many limitations and biases. For example, based on species-specific or individual behavioural differences, it can be expected that the sole presence of divers using scuba can scare some of the fish, while others may be attracted. This creates a bias in the species counts. Moreover, diving-based visual census can only be performed during daytime and at depths of 5-20 meters circa. Deeper dives are possible but with a compromise on diving time and with higher hazard for the divers. Visual census is thus generally limited to the shallowest depth layers and, since considerable biodiversity resides in deeper waters and/or moves to surface at night, the current approach misses on a major component of the system that it is supposed to monitor. While this bias is largely acknowledged by visual census approaches, key target species of interest may go largely unaccounted for, leaving a gap in coastal fish assemblages monitoring. The IMFACT project proposes to complement common visual census applications with an integrated toolbox composed of a Remotely Operated Vehicle (ROV) and a hydroacoustic system. These non-invasive tools are suitable for monitoring fish assemblages in coastal MPAs which require low-impacts approaches. The combination of optical and acoustic sensors permit to sample deeper areas, as well as to monitor larger areas and for longer time compared to traditional visual census. The gears proposed are portable and thus suitable to be deployed on different sorts of vessels, including small vessels which allow monitoring shallow water areas. In addition, the two gears can be relatively low-cost and, as such, suitable also for MPA agencies or scientific monitoring in low-budget contexts such as many tropical coastlines. In alternative, these can be borrowed from scientific institutes who own them thanks to their high portability and versatility.

In theory, the proposed integrated toolbox could make it possible to monitor reef fish abundance in a comparable way to diving-based visual census, and advance the assessment of biomass of aggregations of pelagic fish and other organisms in the water column. In addition, it would enable the monitoring of previously understudied deeper reef and coastal areas in the crepuscular zone, and would permit to monitor the day/night vertical migration and inshore-offshore migrating behaviour of fish and plankton. The IMFACT project proposes a pilot study to assess and verify the feasibility of these approaches in practice.

We developed our project in the MPA of Bonaire (The Netherlands) as a case study. Bonaire, an island in the Caribbean currently recognised as a special municipality within The Netherlands, has a well-established and functioning MPA with perfect environmental and logistic characteristics for our pilot study, which enabled an optimal benchmark for our methods. The island moreover offers a very interesting case study and contacts with the local stakeholders proved very useful and promising.

The goal of the project was to assess in a qualitative and semi-quantitative way whether the proposed approach would indeed be practically feasible and useful, from a logistic perspective and in terms of its capability of providing results of a sufficient quality for analyses, to effectively be utilised in the future to propose structural scientific surveys in coastal areas around the world. This was measured in terms of the toolbox's efficacy in addressing count bias in traditional visual census, and in extending the capability to monitor fish in coastal areas into depth and in night conditions.

Project objectives

Our proposed integrated approach complements traditional diving or snorkeling-based visual census, providing a holistic picture (covering areas, species and mechanisms under-surveyed by visual census) and more accurate estimates of fish abundance (accounting for observation bias intrinsic in visual census). Our project scoped three objectives:

1) Identify and quantify bias in visual census (e.g. fish escape response triggered by visual census operated by a snorkeler), through ground-truthing using the hydroacoustic array.

2) Explore the feasibility of a) monitoring fish in deeper coastal waters (ca. 30-80 m) with both tools, extending to previously under-monitored areas, while reducing the risk for human operators; b) utilizing the hydroacoustic array to monitor pelagic fish in the water column and c) monitoring fish inshore-offshore nightly migrations.

Finally, 3) we planned to develop a protocol for integrated monitoring based on the results.

The effective achievement of the proposed objectives was measured in terms of qualitative and quantitative metrics. Objective 1 was measured in terms of the toolbox's efficacy in addressing count bias in traditional visual census (snorkelling was proposed in lieu of scuba diving because of the complexity of deploying scuba divers within the limited scope of this pilot project). Objectives 2 was evaluated in terms of the suitability and efficacy of the methods for extending the capability to monitor fish in coastal areas into the pelagic realm, at higher depth and at night. The third objective was reached through the development, evaluation and refinement of a sampling protocol.

Study area

The study was conducted in Bonaire, a tropical island previously part of the Dutch Antilles and currently belonging to the Netherlands as a special municipality (Figure 1). The study area was chosen because it has practical advantages such as relatively low requirements in terms of paperwork, being part of a European country (but outside EU). Paperwork for customs for the two gears proved nonetheless sizeable (See also the Limitations and caveats paragraph). The island is characterised by a well-enforced, long-established MPA protecting the entire coastline, permitting recreational diving and snorkelling on which the island flourishing tourist industry lives. There are only limited areas with restriction to either fishing or diving. The island was chosen based on previous experience (Tim Dudeck, personal communication) highlighting the easy access to logistics (boat rental, car rental) and access to beaches and other structures in case of need, easily navigated area, generally suitable sites at close distance.

The marine park extends from the high-water-mark to the 60 meters depth contour, encompassing the entire coast of Bonaire including the uninhabited islet of Klein Bonaire and the Lac lagoon. The marine park's area of 2,700 hectares is home to important and endangered species such as sea turtles, conch, and sharks as well as globally threatened ecosystems such as coral reef, sea grass, and mangroves.

Figure 1. Map of Bonaire island with main areas of interest and diving sites. Source: STINAPA website/ Petra van den Broek

The Bonaire MPA is managed by STINAPA (Stichting Nationale Parken Bonaire). This body performs both monitoring on land, and underwater under the directives of the Bonairian government. STINAPA emerged as a key stakeholder and contact point for the project and any future scientific activity in Bonaire. In particular, STINAPA suggested study areas and topics (e.g. the evaluation of the restricted areas) and highlighted key area of interest which may be of interest for future collaboration (e.g. monitoring of distribution and spawning aggregation of groupers and snappers) and of key habitat (mangroves) which were spontaneously explored during the project.

In addition to providing information and granting permissions, STINAPA allowed to use their boat and guidance by one of their rangers for one day, cementing relationships and facilitating arrival to protected areas.

Equipment

Boat

All fieldwork was carried out at sea (with the exception of the test on visibility and manouverability in the mangrove channels, performed from the beach). We rented a boat with the company Palm Boats Bonaire (https://palmboats.com/en/), which proved very helpful, flexible and interested in the research. At this point we credit part of the success of this project to the boat and the help and expertise of Palm Boats staff. The boat we used was a Ranieri Voyager 19 (5.8m length) with a 70hp Yamaha engine. The size of the boat was small enough to be highly manoeuvrable and suitable for navigating in shallow reef areas, while being large enough to fit all the gear and operate it safely and traveled relatively rapidly to the most distant destinations. In addition, on day 3 the patrol boat from STINAPA was made available to us together with a MPA ranger as skipper, in order to facilitate the planned monitoring in the restricted area of King Willem Alexander Reserve. More over, for the night tour on day 4, a different boat was rented for reasons of safety and logistics: Palm Boats made available their Ranieri Voyager 26 vessel, with an experienced captain and a sailor, to facilitate night navigation. The boat comes with 400 hp total engine power as well as navigation lights (required by law for night navigation) and desk lights which facilitated onboard operations. The boat offered higher speed, but lower manouverability especially in shallow water. Overall, the smaller boat was the most suitable for our work with less acoustic noise, higher manoeuverability and easier handling.

Hydroacoustic setup

The hydroacoustic setup consisted of four parts: transducer, transceiver, processing unit (laptop) and battery. Designed specifically for mobile use, the Kongsberg WBT Mini transceiver is a small, lightweight and waterproof hydroacoustic transceiver. Combined with the SIMRAD ES38/200-18C transducer with 38 and 200 kHz frequencies and 18° power angle, the system is perfect for monitoring of shallower waters. The transducer was mounted on a stainless-steel pole custom-built at ZMT by Christian Brandt to be lowered into the water if a direct mount on the ship's hull is not possible (Figure 2, Figure 3). The system requires a constant, stable power supply of 12V that can withstand the hazards of mobile boat application. Since modern powerbanks are limited by travel restrictions (max. 100Wh capacity for most airlines) and unavailable for purchase in remote areas, we used a heavy-duty car battery in a travelcase by Wattstunde. This setup provided a safe and convenient power source for the acoustic system (Figure 4). Transceiver, laptop and accessories were further stored and operated within a modified Zarges box to provide a shock and waterproof housing (Figure 5). These prototypes were all co-designed and realized with the help of Epiphane Yéyi at ZMT.

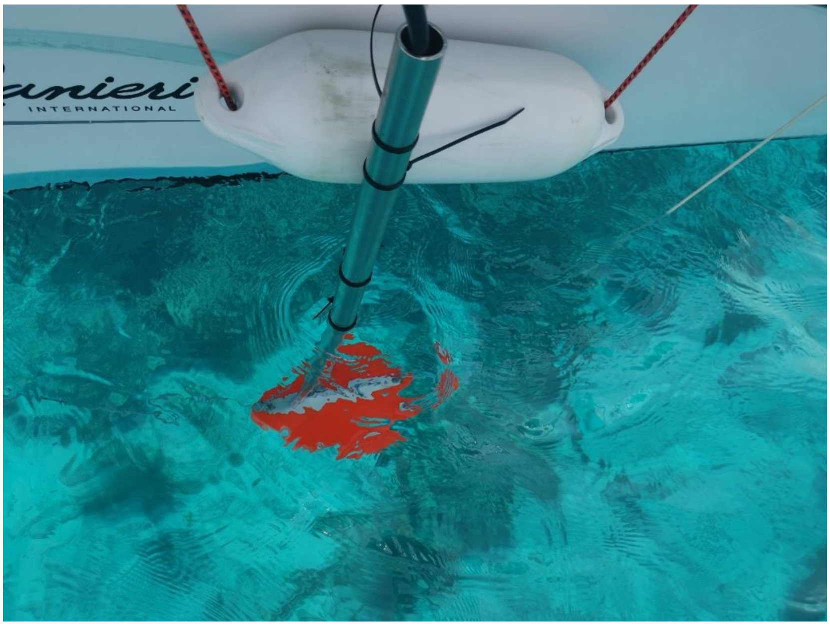

Figure 2. Transducer (orange) and pole mounted to the side of the boat. Licensed under CC BY-SA 4.0.

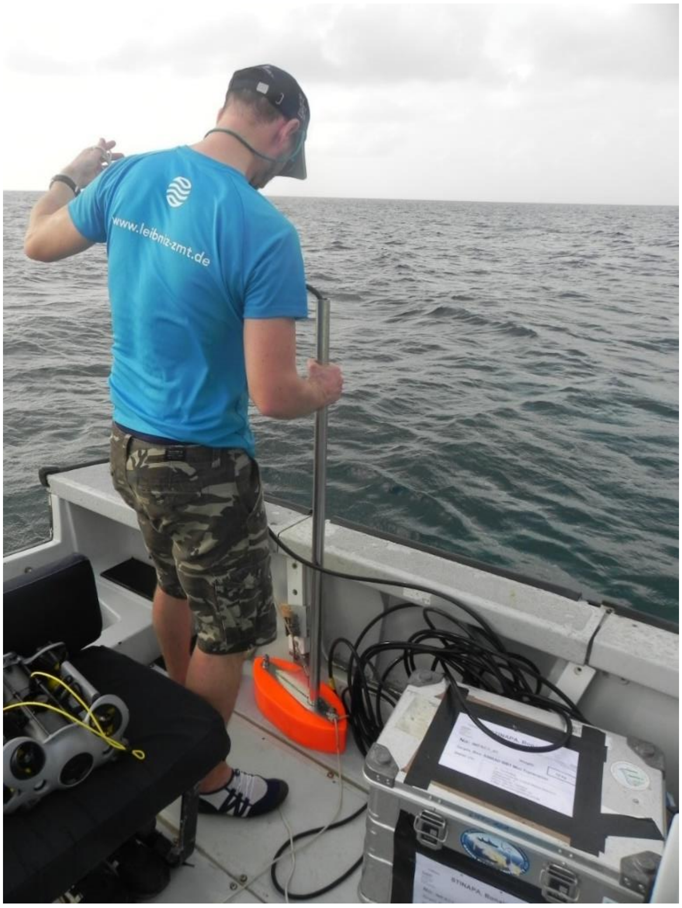

Figure 3. Transducer and pole being deployed on the STINAPA boat. Licensed under CC BY-SA 4.0.

Figure 4. Customised travel case for the battery used to provide a constant power source onboard for the hydroacoustic tool. Licensed under CC BY-SA 4.0.

Figure 5. The signal from the hydroacoustic transducer deployed in the water is being checked in real time on the laptop housed in the Zarges box. The battery casing is visible next to it. Licensed under CC BY-SA 4.0.

ROV

We used a commercial ROV CHASING M2 S (Figure 6). The tool is produced by the company CHASING INNOVATION TECH CO. LTD. (Shenzhen, Guangdong, China) which produces also other ROVs of the same or similar grades. This model was chosen after careful consideration of similar products, specifically for this project. This product was preferred, in combination with its lower purchase cost, also because of previous use in the context of a similar project in Como, Italy (Giovanni Romagnoni, personal communication). In that context, the ROV has been used for monitoring fish abundance through visual census (Romagnoni, in prep.), but never in combination with the hydroacoustic tool.

The ROV was purchased for the present project with the inclusive "advanced set" package which included a travel case, 200 m wire and manual reel, controller, extra lights, charger, spare parts, and two batteries, one with 97 and one with 200 Wh power. Since the 200 Wh battery is beyond the limits of most flight companies which allow to carry batteries up to 100 Wh, it could not be carried on the field. Two extra 97wh batteries were purchased instead to secure sufficient operation time. The Chasing ROV comes with a controller which needs to be connected with a smartphone or a tablet (Figure 7). We used our personal smartphone to connect, after preliminary tests that confirmed it as the best tool.

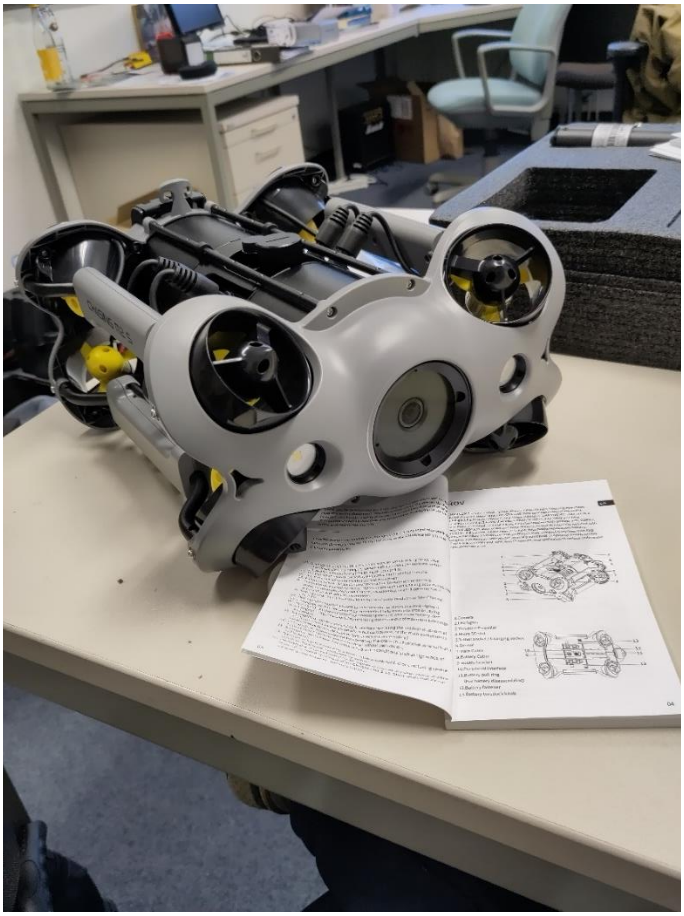

Figure 6. The Chasing ROV. Licensed under CC BY-SA 4.0.

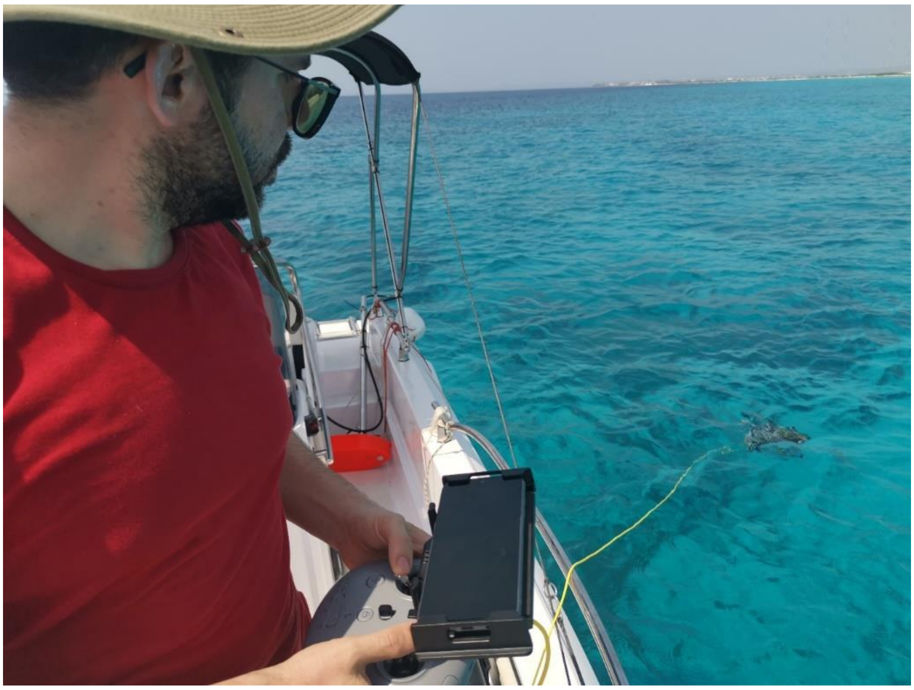

Figure 7. The ROV is connected via cable to the controller and mobile phone. Licensed under CC BY-SA 4.0.

Other instruments used

The project served as a test for the Kobo Toolbox tool which has been promoted by the ZMT Research Data Service. The tool offers a practical method for collecting data and storing them digitally. In the case at hand, it turned out to be very useful in some circumstances, however redundant with paper forms which were quicker at hand and easier to edit on the spot. The Kobo Tool box acted as a backup for the paper protocols in our case, but would have been more practical if a third person was present. The instant mapping of field points was a nice feature.

A field phone provided by ZMT Research Data Service was used for the Kobo Toolbox exclusively and as a general backup.

To mark geographical coordinates of the start and end points of transects, a Garmin GPS handheld was used. The dedicated GPS handheld provided more reliable satellite connection and easy waypoint navigation at sea.

For data storage, we decided to use local storage on the devices while in the field. At the end of every field work session, the data was uploaded to the dedicated data space in the ZMT DataCloud stored on Nextcloud. This proved very practical as a remote backup, also providing a useful pre-designed folder structure and sharing platform for project data.

Fieldwork

Protocols

The project was set up including different types of surveys, some of which specifically designed to address a given questions, while others were structured so to be combined in order to be able to respond to multiple questions.

The IMFACT Protocol for data collection (available in a separate document) outlines all details, however a general overview is provided below and in the Appendix. The survey types were originally designed before being on the field, with the precise intent to be adapted and modified along the way based on the practical experience gathered during the pilot project. Some suggested changes are reported here and further discussed in the section

Summary of findings and in the Appendix.

Sample type 1 was designed in order to quantify the bias of the ROV and of snorkeling-based visual census. This was proposed as substitute of the diving-based visual census. Serial surveys at depth which allowed snorkeler's to count fish efficiently were planned (i.e. 5 meters depth). The survey was based on the idea of counting fish in the same place with the three different methods (snorkeling, hydroacoustic, ROV) to provide a direct comparison.

Survey type 2 was designed on the one side to measure the ROV's bias in counting fish at different depth (i.e. to verify if the bias varies with depth); on the other side it was designed to quantify changes with depth in abundance, biomass and biodiversity, and verify the feasibility to use either of the two tools for such use. It is based on ROV and hydroacoustic transects being run contemporarily at three depth layers. The survey can then be repeated in various areas, including inside vs. outside the MPA, for comparison.

Survey type 3 was designed to test the ROV's capability to efficiently execute transects at greater depth (up to 100 m as per specification of the constructor), to assess if these deep transects can be performed with a standard high enough (i.e. if sufficient visibility, manouverability, and detection power are maintained) for reliably counting fish, and to check the presence of depth-related bias if possible. In addition, the transects were planned to assess the capability of the hydroacosutic tool to monitor fish presence at greater depth. This survey included ROV explorations at pre-established depths, paired with hydroacoustic transects.

Survey type 4 was aimed at collecting information on the pelagic species, both small and large ones. This survey type focuses on hydroacoustic transect, coupled with ROV deployement at necessity. The intent was to either aim for schools in known plausible locations, or using this as "ad-hoc" method to be used during transfers, to then use the ROV for identification of the species of the observed fish schools or individual pelagic fish.

Survey type 5 was a night time version of survey type 2.

Survey type 6 included transects to observe migration, parallel or perpendicular to coastline, with the hydroacoustic tool, and then test with the ROV what species was observed to be migrating toward the surface.

Survey type 7 was planned to be an experiment to test for the disturbance of ROV lights on fish either at night or at depth.

We ran the surveys during the course of five days, with an extra day for an unplanned bonus transect in the mangrove area of Lac at the location called Cai (see map in Figure 1) and an extra evening from the beach, which was mostly used for documentation and exploratory purpose and was not part of the survey.

Field work days

The whole pilot study field work mission lasted six days (Thursday to Tuesday). A summary of the type of transects performed each day is provided in Table 1, while Figure 8 provides the number of transects by depth and gear, and Figure 9 provides the number of transects by depth performed for survey type 2 and 3, the most useful survey types in terms of applicability.

The first day was used as test of the equipment functioning and preliminary settings, with test runs and recording being taken. A two-hours tour allowed preliminary testing the functioning and driving of the boat and of all technical gears and familiarising with the logistics, setups and assembling. Due to the space confinement aboard a small boat, the organisation and planning of the spatial setup of equipment and the chronological order of key actions was crucial both for sampling quality and work safety onboard.

The second day included runs for different types of surveys including (see Table 1) survey type 1 (testing the bias against snorkelling-based visual census), and test run to identify tarpon echoes by visual recognition (survey type 4) performed in a location where large pelagic fish were expected to be found (namely, the wreck of the cargo ship Hilma Hooker, a popular diving destination.

On the third day, we were hosted on the boat of STINAPA to run transects of biodiversity recording at 5, 10 and 20 m (survey type 2) inside and outside the protected area of King Willem Alexander Reserve where diving and snorkelling are prohibited. Unfortunately, a connection issue between the ROV and the controller emerged. The problem affected only the transmission of the visual signal to the smartphone, meaning that the drone was able to dive and record but the pilot was not able to see clearly the real-time transmission, so runs were not fully controlled. Initially, transects were performed despite the occurrence until intermittent connection allowed. As connection worsened, the transects were interrupted to avoid the risk of collision with corals, and thus only hydroacoustic sampling was performed. An *impromptu* snorkelling-based count was implemented for comparison *in lieu* of the ROV-based visual census. This allowed to refine the comparison between snorkelling-based visual census and hydroacoustic system, and the transects were sufficient in number and quality for inside vs. outside reserve comparison.

Day 4 revolved around the evening trip that was preliminarily planned for this day. After restoring the ROV connection through technical tweaks, the morning and early afternoon were used to run transects in shallow waters at the location were the evening trip was planned (using survey type 2), in order to offer a day-night comparison of the same site. Deep dives were also tested with the ROV (survey type 3). A long hydroacoustic transect between the main island and the island of Klein Bonaire was also performed, to be compared with the night transect in order to investigate day-night vertical migration of fish and plankton layers (survey type 4). The night excursion included corresponding transects (survey type 5 and 6), mostly hydroacoustic ones, as the ROV could not be deployed because of logistic reasons (wind and currents putting a hazard to navigating in darkness in slow speed required by the ROV piloting), coupled with cable entanglement. The few seconds the ROV was in the water, its light attracted plankton to an amount making it impossible to see.

On day 5, we performed additional deep water transects with the ROV to crystalize its capacity to effectively perform visual census at high depth (survey type 3), and also tested the effects of light levels (corresponding to survey type 7, combined with survey type 3 transects); and successfully completed the search for barracuda and other schooling fish by the Salt Pier.

On day 6, a rapid experimental trial set in the site of the mangrove area of Lac, in the site of Cai, allowed to experiment with running the ROV in the mangrove channels. Questions about the applicability of the ROV in this environment and its capability of counting small fish, without lifting sediments and compromising visibility, were casted by STINAPA personnel who was very interested in the nursery role of this habitat which is protected and of high interest for multiple stakeholders. The ROV was thus tested for its use in shallow water and for the issue of sediment lifting. The ROV performed well (despite additional connection issues with the main cable), with very limited impact of its propellers on sediment lifting and visibility. It could safely navigate in water as shallow as 50 cm, and clearly avoid obstacles in the channels (without entering the root stilts) and count fish efficiently.

Table 1. Performed surveys by type per day

	Survey Type 1	Survey Type 2	Survey Type 3	Survey Type 4	Survey Type 5	Survey Type 6	Survey Type 7
Day 2	4			4			
Day 3		9					
Day 4: daytime		8	3	1			
Day 4: nighttime					2	2	
Day 5		5	6	6			8*
Grand Total	4	22	9	11	2	2	

*transects run for survey type 3 on Day 5 are also effectively used for survey type 7, being reported separately in the table but corresponding in practice.

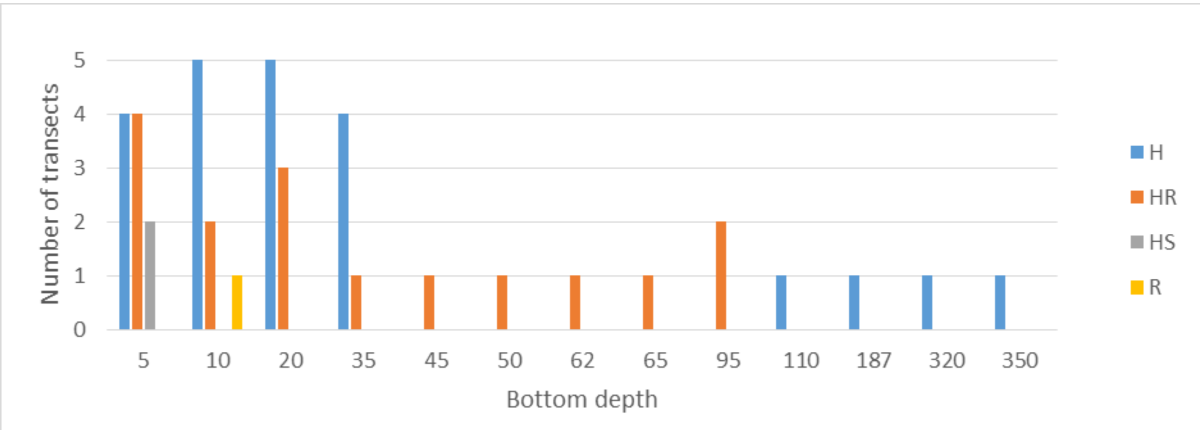

Figure 8. Number of transects by depth and gear including hydroacoustic (H), ROV (R), and combination of the two (HR) and hydroacoustic with snorkeling (HS).

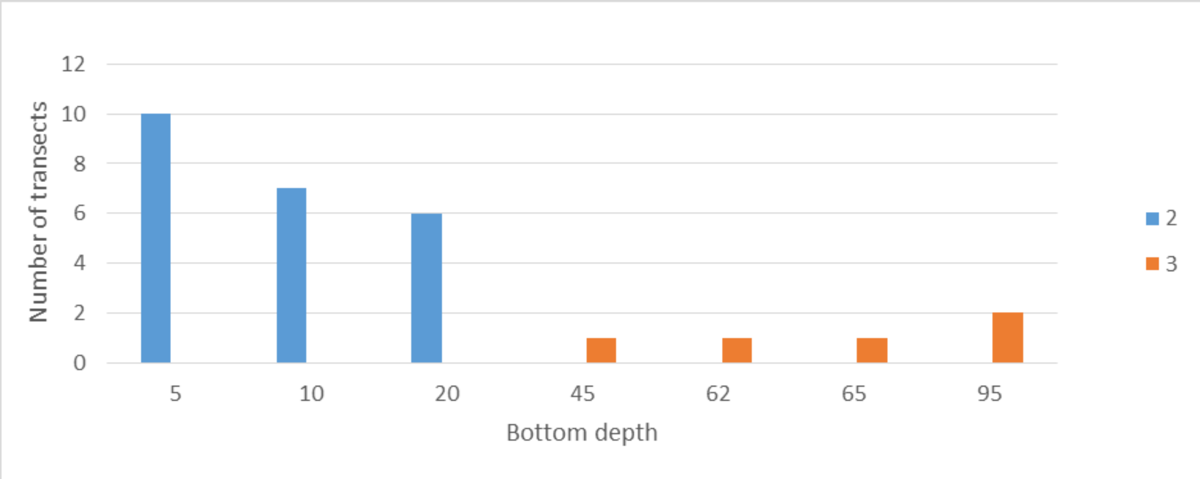

Figure 9. Number of transects by depth and transect type 2 (blue) and 3 (Orange).

Results

Results are reported here structured by the respective objectives and sub-objectives.

Objective 1

The first objective addressed the identification of bias in the sampling of both the ROV and the visual census performed through snorkelling. The question was on the one side whether it is possible to evaluate or calculate bias; on the other side, the goal was to attempt to quantify the bias. The quantitative evaluation was hardly attempted in a systematic manner because of the challenges encountered on the field (detailed in the following). Quantitative comparison between tools are the subject of ongoing statistical analyses (not reported in the current report). In the next section, qualitative description of the bias as well as reflections on the question on whether bias evaluation is possible are reported.

ROV bias

The original plan was to attempt measuring the number of fish beyond the visual field of the ROV through directly monitoring the ROV using the hydroacoustic tool. In this terms, it was not possible to systematically calculate bias following the ROV with the hydroacoustic array as it was very difficult to follow the ROV navigation with the boat, and thus maintaining it within the hydroacoustic beam. In particular, wind and current moved the boat and ROV in different direction, challenging our capacity to retain the boat on the same position above the ROV. Efforts to avoid the ROV cable to get entangled in the engine represented an additional challenge. However, experience helped and after substantial effort on perfecting coordination and communication on board during ROV navigation, through the course of the days this operation became easier and more efficient. On the last day, careful handling of the boat position allowed to directly observe the ROV on top of fish schools or embedded in it. In this case it was possible to directly observe mild avoidance behaviour of part of the school. It was not possible to count individual fish and compare this count with that of the ROV, because individual fish count with hydroacoustic gear is not so straightworward in large schools. The observed scare response to the ROV, as well as attraction to it, was also witnessed with the ROV videos: in numerous cases, fish tend to be curious toward the ROV and approach it, to then, in some cases, move away when the tool approaches. This was observed for pelagic species such as jackfish, barracudas and tarpons which actively approached the ROV and stayed in close proximity, in the case of the jacks actively following it (Figure 10).

Only close approach to the barracudas and tarpon caused a moderate escape response. In the case of jacks and barracuda, when the lights were turned on the fish were startled and reacted to immediately recover their position (Figure 11). For all species, the initial curiosity faded away with some minutes when the schools moved off or dissipated. Notably, for individual fish (tarpons, and one solitary barracuda) the same curiosity was observed. The curiosity of large pelagic fish for an unknown object is expected and unsurprising, and it may result in a bias when the transects are performed for investigating fish density; however, for the purpose of identification of pelagic fish observed with the hydroacoustic this may actually constitute an advantage.

Figure 10. A school of jackfish approaches and inquisitively encircles the ROV, sticking around it for more than one minute and following along when the ROV moved away. Licensed under CC BY-SA 4.0.

Figure 11. The jackfish startled reaction at the moment the ROV lights were turned on, visible with shining reflections on the fish bodies, triggering a rapid and short-lasting escape reaction. The fish immediately recovered their position and kept swimming next to the ROV. Licensed under CC BY-SA 4.0.

In contrast, demersal fish exhibited less attraction and rather a mix of indifference, mild avoidance, or initial curiosity that left place for fear when the ROV approached. For example, one large fish (possibly a snapper) at Salt Pier in the deeper transects (50 m) approached the ROV frontward to then dash away when the ROV moved in its direction (Figure 12). Fish whose swim trajectory was not directly toward the ROV swam away more slowly. Perhaps the speed of the ROV may influence the escape response and thus the visibility: tests on the effect of the speed of the ROV may help to understand whether slower cruise speed allow to count more fish and, in general, whether speed is an element influencing the fish response.

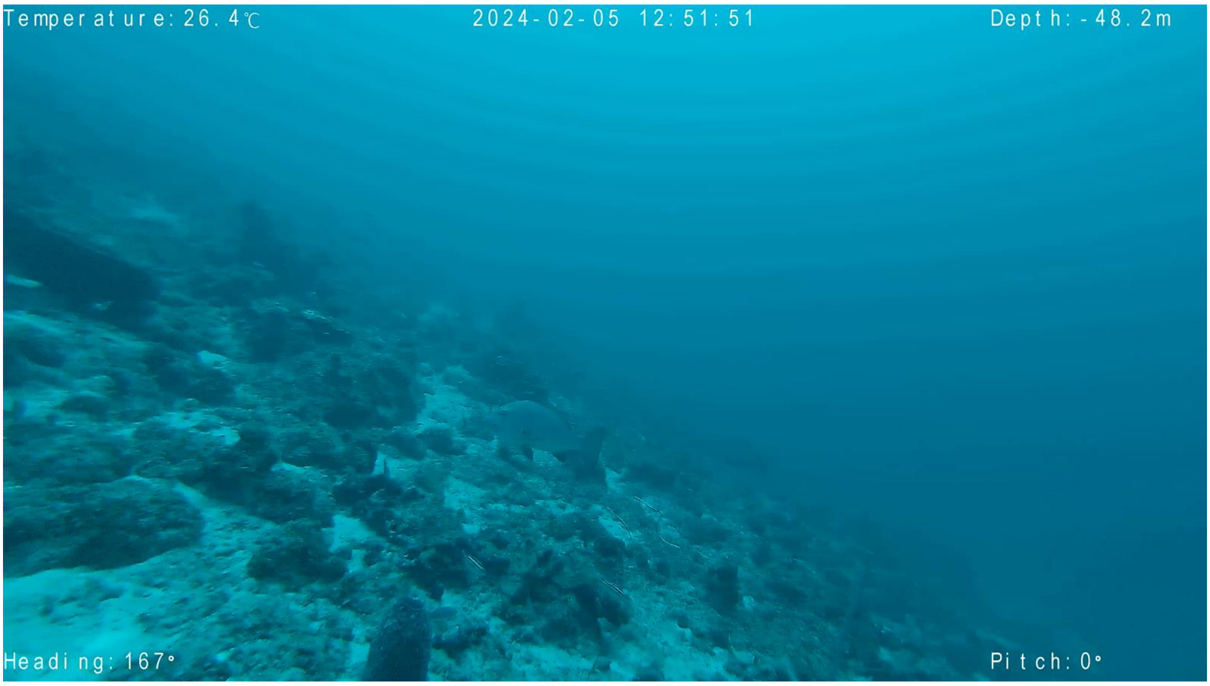

Figure 12. A large fish, likely a snapper, approaches the ROV frontally before suddenly taking off in an apparent scare reaction.

Building experience as well as a third person that helps with navigation may be needed and could substantially improve the capability of directly monitoring the ROV and, thus, measuring quantitatively the bias. As an additional factor, the angle of the transducer is relatively narrow, so that at the shallowest depth the exercise is more complex while keeping the ROV under the control of the hydroacoustic array could be easier at depths around 20 or 30 meters as done in Day 5.

The statistical analyses (to be developed in the future based on the data collected during the fieldwork) may reveal further insights.

Snorkeling bias

The assessment of bias caused by snorkelling visual census was a proxy for the assessment of bias caused by divers, which was not possible to conduct because of logistic and bureaucratic complexity of organisation of diving within the course of this project. Snorkeling however does not compare in full to diving: the principle was that divers would scare the fish due to noise, which snorkelers may not do. Moreover, it was not possible to monitor the snorkeler under the hydroacoustic beam because snorkelers are at the surface. These caveats strongly limit the usefulness of this comparison. However, the experiment could have provided some interesting insights. Ultimately, snorkelling-based visual census was not easy either because of little training on this skill: fish count was difficult for untrained snorkelers, and only a limited number of transects were performed, limiting the capability to build experience. Due to the difficulties in counting all fish, an alternative approach was proposed, consisting of only counting parrotfish, which are more conspicuous and less abundant. However, the hydroacoustic tool was not suitable for counting parrotfish as it cannot reliably identify fish species or families. The comparison of fish count between snorkelers and hydroacoustic transects in parallel in the 5-10 m depth layer was attempted, assuming on average the same environment and thus roughly the same fish community would be covered; as such, difference in numbers on average would be attributed to one or the other sampling method. However, the survey design was not robust and sample size very limited.

Hydroacoustic bias

The hydroacoustic tool was not originally planned to be tested for bias, however it rapidly emerged as an option. A comparison was attempted between visual census and hydroacoustic readings both with moving boat and with still boat. The concept was to count how many fish the hydroacoustic detected compared to how many were actually there as observed by the snorkeler (used as a ground-truth).

The moving boat bias check was improvised and, as such, not robustly planned: the snorkeler was counting fish, being followed by the boat. However this proved inefficient, as it was impossible to check how many fish the hydroacoustic tool would count. It would be better to reverse the scheme, with the snorkeler following the boat rather than leading. This would allow to verify the number of fish swimming under the beam, to then compare these numbers with the hydroacoustic reads and thus estimate bias of the hydroacoustic transect. However, this type of test was not attempted because of limited time. An additional person is also required for this type of simultaneous observation as the person monitoring the hydroacoustic reads must focus entirely on this, and thus cannot drive the boat.

An alternative was performed with the boat being still, tied to the buoy over the reef in 5 m depth. This test effectively allowed to count fish in the water under the boat (as per visual observer) vs fish counted by the hydroacoustic tool, both at the bottom and in the water column, highlighting some blind zones in the first meters from the bottom and from the surface. This is in line with common hydroacoustic practices and statistical processing. Schooling fish were generally observed by the echosounder if deeper than 1 m. This is due to an acoustic deadzone near the echosounder that arises from physical and technical interferences at the echosounder surface. It is frequency dependent and adds to the noise that disturbs the acoustic signal coming from wave action, boat vibrations and electrical noise. We found that for the 200kHz data fish below 1m depth could be statistically sampled whilst for the 38khz frequency this extended to 2.8m depth. However, it is a common procedure to exclude the first 3 or more meter water depth anyway due to the proximity of the boat and the small sampling area. The latter refers to the angle of the hydroacoustic beam results in a very small beam surface in the first few meters of depth, hence only few of the fish spotted by the visual census operator are actually entering the observation field of the hydroacoustic. Notably, however, fish at the bottom were hardly visible for the hydroacoustic tool when they were hiding among the corals, being basically not detected in the first meter by the bottom, and becoming visible when dashing upward off the corals.

The exercise suggests that bias in the hydroacoustic capacity to count fish can be estimated through properly crafted exercises. These need more experiments and practice in order to effectively design robust tests capable of detecting and quantifying biases of the hydroacoustic tool. It is standard procedure in hydroacoustic surveys to exclude areas near the bottom and near the surface (by comparison, it is common to exclude 10+m near the surface and 3+m near the bottom on standard surveys) and the diverse habitat of coral reefs makes the exact determination of bottom and near-bottom exclusion zone difficult. However, to determine reef fish abundance more accurately, this needs to be worked on and requires more practical experience.

One key point is that boat noise scares the fish away. This emerged clearly when observing the escape responses on the monitor (downward trajectories of the fish when the boat approached) and is consistent with current knowledge about fish behaviour. This factor was not previously considered and it may affect the way the survey needs to be built. In theory, deeper transects may be less affected by this aspect, with the noise bias something to be factored in survey design. The comparison between the moving and standing boat, and perhaps standing with engine on or off, may be something to be explored further.

Objective 2

This Objective focused on exploring the feasibility of monitoring fish in coastal waters. This goal is addressed generally in this section, and with more detail for each of the three sub-objectives in further sections.

In general, the survey confirmed that fish can be effectively and efficiently monitored in coastal areas with the two tools individually in some respect, and that the combination of the two tools offers a powerful approach informing each other and complementing the respective limitations. Combined, the set of tools, through well planned sampling design, can efficiently inform about fish abundance and biomass well beyond what commonly used divers-based visual census can.

Firstly, we show that the hydroacoustic setup can effectively count fish in shallow water as shallow as 5 meters, on the reef shelf and on the break, provided that the boat characteristics permit moving in the reef (Figure 13). This is, to our knowledge, the first attempt to monitor fish in such shallow water using portable professional hydroacoustic tools. The limited cone width does not impede fish detection from 1 m depth even if the narrow cone may restrict the breadth of vision. The extensive effort in power management developed within this project (see section Successful aspects) allowed to make the whole setup independent and self-sufficient. The gear itself is portable and applicable to various settings: we used it on three different boats.

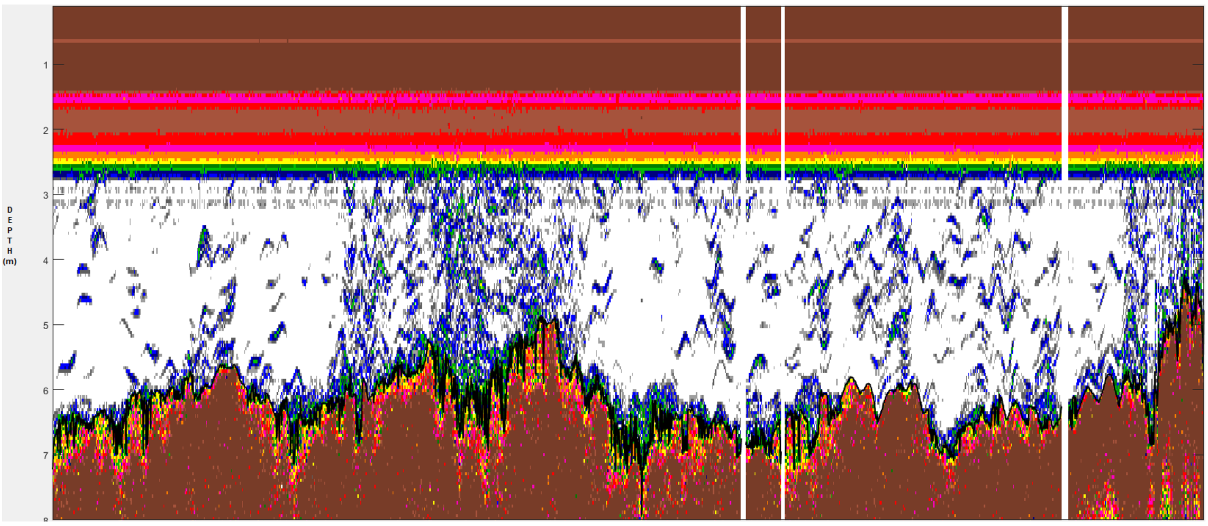

Figure 13. 38 kHz echogram showing individual small fish (blue shapes) and fish groups at shallow depths of 6m. Notice the black, thin line representing the detected bottom, the white vertical lines indicating removed pings (no data) and the acoustic surface deadzone (horizontal red and pink stripes) up to 2.8m depth. Licensed under CC BY-SA 4.0.

The only limit for hydroacoustic sampling is the surface deadzone and the obscurity in the reef as the corals hide fish at the bottom so only fish above 1 m from bottom are observed. It however sampled the whole water column, so to provide a real-time view of the whole fish community of the reef (Figure 14), rather than just the bottom ones in contrast to the ROV, but also to divers-based visual census, thus reporting additional valuable information.

The ROV can observe and count fish at 5 m and below or even shallower. Its speed, tilt and cruising pattern may influence fish detection as it can only see in a certain direction and angle. The angle and direction of observation can however can be controlled, speed can be reduced, and direction monitored through the in-built compass. The main challenges of the use of the ROV include difficulty in maintaining the direction both for controlling as it tends to turn, and difficulty in depth navigation due to bottom tridimensionality. To avoid corals during navigation, one may need to manoeuver around or above outcrops, compromising the regular distance and direction of a transect. Distance from the bottom is critical for the capability of identifying fish which directly below the ROV; at the same time, if tilting the camera front-ward, fish may go undetected when too far. There is therefore a trade-off between visual range and a detailed view of the bottom below the ROV.

All in all, the two tools show promising opportunities for the development of a monitoring system for coastal fish assemblages. The hydroacoustic tool could efficiently count small and large pelagic fish, in several cases being able to identify the species upon visual cross-comparison and verification with the ROV. Coupling between the two tools enhances the respective capacities, making them exponentially more powerful. In particular, the hydroacoustic gear is highly effective at counting fish schools at the 10-20 m shelf break as well as large pelagic fish such as barracuda. In this respect, a broad-scale, coast-wide survey to monitor fish abundance and biomass along the whole area of, for example, Bonaire island would be feasible when properly planned.

The hydroacoustic was able to count tarpon and barracuda well, being capable of estimating the right number for tarpon 2 (+-1) as witnessed with the ROV. Tarpon tend to occur in small groups of 2-5 individuals making counting easy. For larger schools of highly mobile fish, such as greater schools of barracudas and jacks, the hydroacoustic underestimated the number since only a fraction of the school enters the hydroacoustic beam. On Day 5 at Salt Pier, the ROV counted over 20 barracudas while the hydroacoustic system counted 7; however, this comparison does not imply a lower capacity of the hydroacoustic as the numbers are not standardised by surface monitored or time (a necessary step for analyses). Moreover, it must be said that, given the implemented protocols, the ROV would have not counted the barracudas at all without the detection by the hydroacoustic since the school was midwater about 20m above the bottom, while the ROV was generally operated at the bottom, thus missing this and other schools. It is this synergy between the combined tools that allows for a much more accurate depiction of the fish stocks.

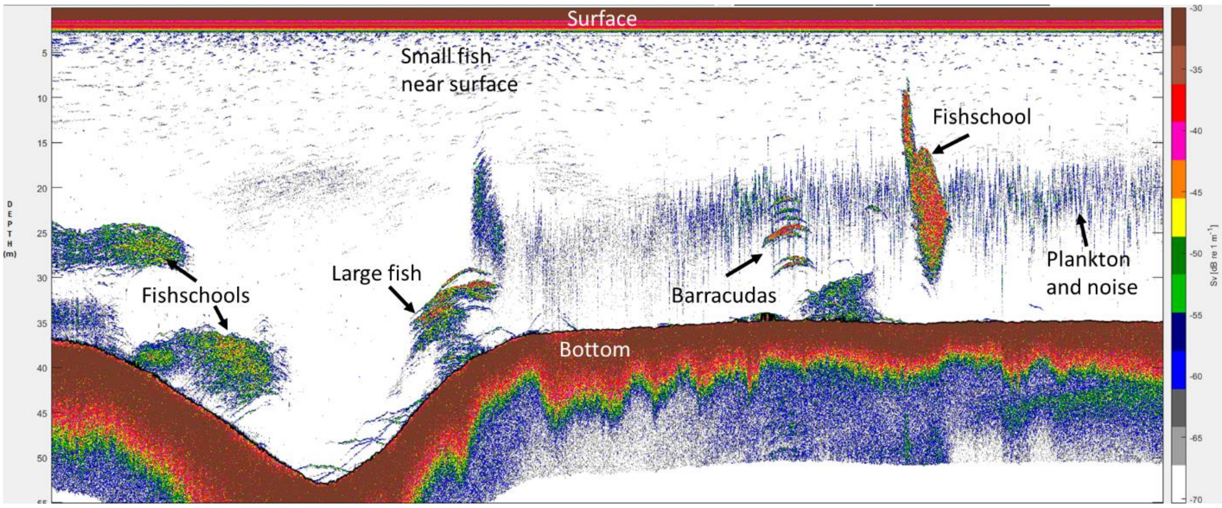

Figure 14. Echogram showing the multitude of fish signals in the water at Salt Pier station. Large fish can be clearly distinguished by the sickle shaped echoes from smaller fish and schools. Licensed under CC BY-SA 4.0.

The ROV returns good quality images but might be inferior to human eye and thus to a diver-based visual census in the capability to capture small fish, especially when in distance. Screenshots from the ROV videos proposed in Figure 15 and Figure 16 exemplify this showing the challenges in identifying small fish (notably, video transects allow however higher identification power than screenshots). This might be a technical limitation and possibly a higher quality ROV camera can resolve this problem easily. It could also be enhanced with sophisticated post-processing tools in the future. However, video quality does not generally hinder accurate fish count but rather species identification in low light condition. Especially for medium to large fish, fish count tends to be accurate, while it may be less accurate for small and very small, cryptic fish.

Figure 15. A colourful coral reef with multiple small cryptic fish. Licensed under CC BY-SA 4.0.

Figure 16. Limited contrast between the fish and the background bottom make fish count challenging, but not impossible. Licensed under CC BY-SA 4.0.

Setups of tilt, speed and distance of the ROV from the bottom can influence the performance of the transects, and their definition need further testing and experience. Other technical issues include manoeuvering and maintaining the direction, while speed and depth control, as well as the control of fine movement, are of impressive quality. In fact, the cable and cable winch were the main problem during release and retrieve of the ROV, and hampered the survey due to repetitive clogging. Communication with the manufacturer is ongoing.

In the following, some detailed specifics of the sub-objectives are provided.

Objective 2a

This objective focused on exploring the feasibility of monitoring fish in deeper coastal waters (ca. 30-80 m) with both tools.

The ROV deep water transects proved to be viable and were very successful. Visibility was excellent and counting fish was easy (Figure 17, Figure 18, Figure 12). Hence, the capability to monitor fish abundance through structured transects of high quality at 40, 50 or 60 m depth and even at 90 m was therefore confirmed. However, the use of lights did not improve vision, and instead they had an effect on the fish behaviour: fish were surprised and reacted startled without escaping as a consequence of the presence and onset of light. As an additional value, the deep dives can be used not only for monitoring fish, but also for corals and sponges counts and habitat characteristics (Figure 19, Figure 20). Stakeholders (in particular STINAPA) expressed a genuine interest in that since estimates of coral diversity and abundance could only be estimated from rare technical divers' observations, and the use of ROV dives may provide a substantial improvement for monitoring capacity.

Figure 17. A porgy (possbly saucereye porgy) rushing out of the ROV's way. Licensed under CC BY-SA 4.0.

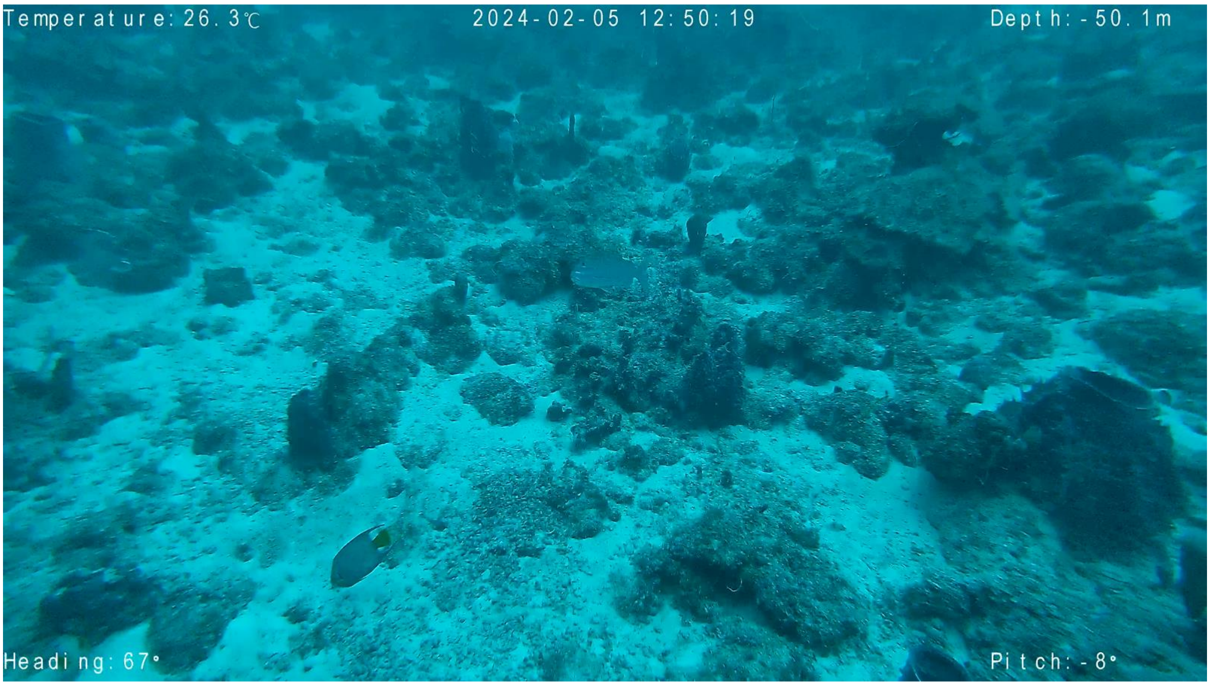

Figure 18. A porgy (centre of the image) and a pair of angel fish (only one visible in this frame) observe safety distance while circling around the ROV with apparent curiosity, before continuing about their business. Licensed under CC BY-SA 4.0.

Figure 19. An unidentified organism (plausibly a crinoid) clings on to a barrel sponge and provides shelter to a small fish at 48 m depth. Licensed under CC BY-SA 4.0.

Figure 20. Barrel sponges, ramified sponges, gorgonians and bamboo corals dot the landscape and offer shelter to fish even at depth. Licensed under CC BY-SA 4.0.

The hydroacoustic had similarly good capacity: it was easy to monitor individual fish and schools at or near the bottom at the same depths the ROV was monitoring, which made it possible to compare the two tools. Naturally, the hydroacoustic could monitor at the same time the whole water column, as well as reaching down to depth well beyond those to which the ROV is limited to, extending the capability of acoustically monitor fish abundance at depth (Figure 21).

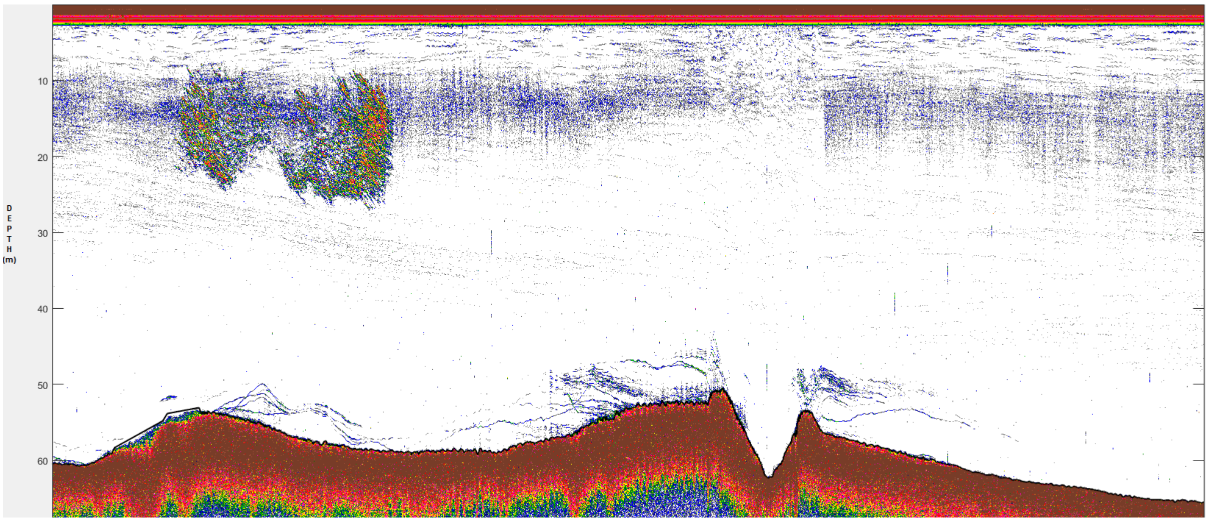

Figure 21. Echogram at low speed showing pelagic fish schools as well as individual fish at the bottom between 50 and 60m depth. Note: Each line is the trajectory of a single fish near the bottom. Licensed under CC BY-SA 4.0.

Objective 2b

This objective focused on exploring the feasibility of utilizing the hydroacoustic array to monitor pelagic fish in the water column.

Observing pelagic fish in the water column was very effectively achieved using the hydroacoustic system (see also Figure 14 and Figure 21). In principle, this is where echosounders shine as they detect even small particles in open water space. As mentioned for objective 2a, the school of barracudas would have gone unnoticed by the ROV since its visual detection is limited to a certain viewing angle. This is also true for the echosounder pinging downwards only, but it is not limited by light or depth. In the pelagic, open water realm, most fish tend to school and are not evenly distributed, so the chance of missing them is high. Higher sampling effort is thus required. Here, the easy deployment and constant monitoring of the echosounder is key as it can operate while the boat moves even at higher speeds. This is also the reason why hydroacoustics surveys are key indicators for pelagic schooling fish like herring and mackerel when it comes to stock status and fishing quotas.

Objective 2c

This objective focused on exploring the feasibility of Monitoring fish inshore-offshore nightly migrations. Two types of explorations were performed: investigation of the presence of nightly migration from deep water to the surface (i.e. a deep-water scattering layer), through hydroacoustic transects, and exploration of changes in community composition along the shelf break. The latter was initially conceived as an exploration to be performed with both the hydroacoustic and the ROV, although the latter was acknowledged to result in likely bias due to the attraction-repulsion effect of lights. Irrespectively, the ROV could not be operated successfully due to various reasons as detailed below. Both types of exploration required a day-night comparison, so similar transects were run during the same day at day time and night time.

For the exploration of the deep-water scattering layer, day and night hydroacoustic transects were performed successfully. These showed pelagic assemblages at depth during both times. Strikingly, these were found at a certain distance from shore between bottom depths of 50 to 200m. Figure 22 shows this lateral structuring between Bonaire and Klein Bonaire. A first appearance of deep scattering layers was later identified as false bottom echoes (originating from acoustic pulse lengths too short for the increasing depth). The depth was excessive for the ROV to be deployed, so the assemblage pattern was not visually verified and it could not be identified which species formed schools in deep waters. However, we could distinguish deep water schools of fish and plankton layers by their hydroacoustic characteristics. It is a question for the next project to identify them, possibly from a stationary boat.

Notwithstanding, the echograms in **Error! Reference source not found.** reveal vertical migration in he upper 50m. While during the day (**Error! Reference source not found.**a), plankton and fish were aggregated in a slim, condensed layer at about 15m depth, during the night (**Error! Reference source ot found.**b), organisms were more evenly distributed vertically between 0 and 70m depth. The ROV did also observe small-scale vertical movement of plankton during the afternoon which could be an indication for the onset of vertical migration in the upper water column.

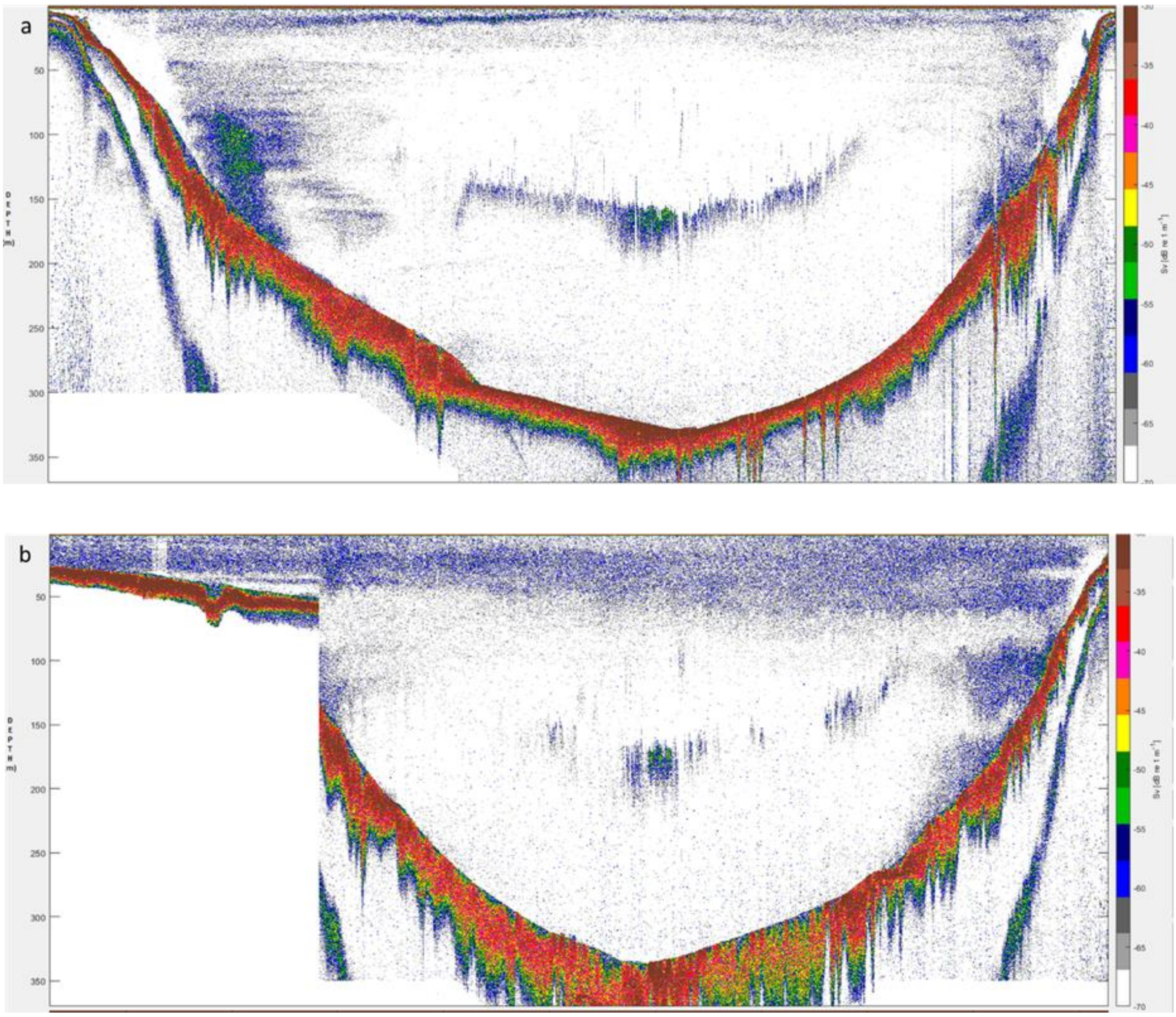

Figure 22. Day (a) and Night (b) transects across Bonaire and Klein Bonaire. Note that the central layer of echos in the middle of the echograms are likely false bottom echoes and not organisms. In b), the pinging was stopped and settings changed, which is visible as a cut on the left side of the echogram. Licensed under CC BY-SA 4.0.

The hydroacoustic-based day-night comparison on the shelf break pointed at different composition: the schools, which were constantly observed at the shelf break during day time, were not observed at night but instead few, large fish were seen. This suggest a migration at night consistent with our expectations and shows we can measure this behaviour and estimate biomass and abundance changes. It must be stressed that the night-time survey was performed with a different boat, providing possibly a bias, and the differences cannot be unambiguously attributed to the day-night difference (remaining our working hypothesis) rather than the boat characteristics. Nonetheless, the possibility of investigating this difference is clearly demonstrated through the use of the hydroacoustic. The ROV, on the contrary, could not be deployed because of safety issues (strong wind causing challenges to manouvering in a safe way out of the reef) and to the ROV cable entanglement. In addition, when the ROV was placed in the water, the plankton was attracted to it immediately, aggregating around the lights and rendering the visibility so limited that it was impossible to detect anything. For this, further tests are needed with the ROV to assess whether it can be used effectively at night.

A night test from the beach, performed *ad-hoc* and simply for documentation, allowed to show that swarms of plankton were strongly attracted by the lights (Figure 23); this in turn had attraction behaviour for other fish that moved just out of the light cones, profiting of the possibility of preying.

Figure 23. Swarms of plankton attracted by the ROV light almost obscure the presence of a mooring concrete block in a shallow water night test from the beach. Licensed under CC BY-SA 4.0.

Figure 24. A large tarpon, a visual predator, lurks at the edge of the light cone in the hope to snap some preys. Licensed under CC BY-SA 4.0.

Summary of findings

Successful aspects

In summary, the IMFACT projected aimed at measuring the toolbox's efficacy in addressing count bias in traditional visual census, and in extending the capability to monitor fish in coastal areas into depth and in night conditions.

Main Success aspects:

- Batteries and power management: the project designed and tested prototype solutions for power independence and management, allowing the set of tools to be fully operational off-grid on a small vessel. This provides full capacity to operate in any area of the world, provided a car battery is available and overnight charging is possible, and extending the range of action of the hydroacoustic in particular to previously unmonitored areas.
- Technical setup: The hydroacoustic gear is fully transportable and adaptable to different vessels, with the pole being easily tied up to the side, and capable of sustaining navigation speed of 3kn and more. The setup of the laptop, casing and battery was functional and even able to withstand an accident when water flooded part of the boat. The battery casing was not damaged and the laptop casing helped protecting the gears from splashing. The custom-made technical setup was thus successfully tested.
- Improved capacity of monitoring fish abundance: monitoring in shallow reefs, deep water, and at night was possible thanks to either of the two tools, and in many cases the tools' capabilities were enhances by the coupled application. The principle example is that of the identification of large pelagic fish such as tarpon and barracuda that were firstly observed through the hydroacoustic tool, and later identified at the species level through visual observation with the use of the ROV. Neither of the two tools would have reached this goal in

isolation. This shows that the combination of the two tools can greatly extend the capability of MPA and coastal fish monitoring well beyond the current range of visual census.

- Mangroves exploration: Upon suggestion by our key local partner, an attempt to use the ROV to explore fish abundance in the mangrove channel, in a key area of conservation interest for the local conservation bodies, was attempted. The request was to assess if the ROV can count fish effectively without lifting mud and sediment. This was performed very successfully, opening new avenues for the use of ROV for fish monitoring in very shallow areas.

Limitations and caveats

The pilot study allowed to identify several points that may need to be considered in future applications, both in terms of limitations, in weaknesses of the approach or the tools, or in aspects that could be improved through simple updates in the methodology.

The use of the ROV allowed to highlight key issues with this product in particular, which may however need to be considered in the future also in the use of other ROV models:

- Light is very bright under tropical sun, and this represented an issue for proper vision of the monitor from the pilot, for which a dark context would be better. While a small shade is available with the ROV controller, this was insufficient. We used a towel, hiding under the partial darkness to provide better visibility for the pilot (Figure 25). This ad-hoc solution worked well, however it has the drawback that the pilot could not observe the surroundings for navigation, nor communicate effectively with the other operator. Alternative options could be considered.

Figure 25. Ad-hoc solutions: using a towel to improve visibility of the mobile display used to pilot the ROV under the strong tropical sun. Licensed under CC BY-SA 4.0.

- The battery time of the 95Wh batteries was somewhat limited. Availability of spare batteries allowed to change and redeploy the ROV, but longer deep dives were not possible. Where possible, more batteries, and if feasible of higher Wh, should be used; the 200 Wh however cannot fly (with current air company regulations), so shipping to destination should be considered instead.
- Cable and manoeuvring was the Achilles' heel of the ROV: the cable reel was not functional and entanglement was a continuous hassle. Manual reeling in and out was also not as practical because it led to further entanglement. While in flat sea conditions this is a nuisance, in high wave conditions it may represent a danger for safety and for the gear itself. Better technology for the reel and for its retrieval is needed. In addition, the cable was prone to damaging, as twice during the 6 days of fieldwork we had to interrupt the work due to connection loss. A spare cable would be useful, as well as clear understanding of the handling practices that may risk damaging the cable (e.g. pulling or washing). Manouvering the boat around the cable in order to avoid entanglement in the engine required substantial skills which were only built after some days. A third person onboard would help tremendously.
- The relatively low-quality resolution of the images was somewhat less than expected: in most videos blurred images prevented full identification of most fish. Perhaps the tool is sufficiently valid for fish count, while alternative options with higher-grade camera or post-processing could be used to refine the capability of fish identification skills.

The hydroacoustic tool has very little observed limitations, due to the profound knowledge of this tool and of its capabilities that one member of the team sported. The main challenges encountered were:

- Scarce capacity of the hydroacoustic tool to reliably count fish at or near the bottom when this has a strong tridimensionality (i.e. in coral reefs). However this is hardly a new finding and it was expected: in the hydroacoustic field it is standard practice to discard signals coming from within 3 m from the bottom. Conversely, our approach showed that the tool can be reliable from 1 m, i.e. roughly the depth of the coral boulders encountered, and that this limitation can be quantified through visual assessment.
- The capacity to distinguish the number of fish in schools is somewhat limited by the setup (especially the speed of the boat) and the thickness of the school (Figure 14). Estimation of biomass rather than number of fish may provide a better measure, however this might be difficult to compare with number-based visual census. It looks best to use the biomass of a school as a proxy to then estimate number of fish of the school by dividing it through individual fish biomass estimates.

In addition to the technical issues, some aspects of the monitoring may be limited and present some caveats that have in part been only discovered during the fieldwork. These include, among the others:

- The boat noise and its presence and movement may represent a disturbance factor for fish; the effects of such disturbance, and its extent in depth, should be considered and assessed through robustly designed experiments, and we provided examples and attempts that show it can be done using some of the methods proposed.
- Different boats may produce different levels of noise and thus of disturbance which on the one side affect the fish presence and response; on the other, it may result in a different noise profile in the hydroacoustic due to vibrations and electrical noise. This can be accommodated through setup tweaking, however the use of different boats may require some standardisation procedure.

- The possibility to evaluate the bias of the ROV using the hydroacoustic is limited by the capability of the research team to maintain the boat, and thus the hydroacoustic beam, on top of the ROV, which strongly depends on the ocean conditions as well as on the experience of the team.
- The ROV night vision depended greatly on the presence of plankton, which was attracted to the lights to the point of making visibility close to null.
- In many circumstances, it was difficult to manouver at the same time the ROV, the boat, the hydroacoustic, while ensuring that the ROV cable did not get entangled with strong current, and entering data in the protocols. For this reason, it is strongly recommended that a team of at least three people undertake this work. While a local pilot may help, the best solution is if all three have experience or build up the experience necessary for coordinating on board, i.e. have a good understanding of the survey types and the sampling approaches.
- While power management on board was very efficient, charging time overnight might be insufficient, especially when batteries need to charge for 2 hours each and it might be unpractical to wake up every two hours for swapping. A larger set of sockets and cables may be needed, or a longer charging time slot, so to ensure all tools are fully charged without sacrificing surveying time. This might be particularly true in context more challenging than Bonaire, where for example longer travel time between field and an electricity grid is needed, or where power cuts might be an issue. In the case of Bonaire and our accommodation, everything worked out smoothly.
- The paperwork required for transporting the ROV and hydroacoustic was not negligible and required extensive efforts before and at the travel time, including long waiting time at the custom checks both at departure and arrival. Informing the local partners and asking in details the necessary steps (e.g. additional declarations) is always important.

Contribution and relevance to ZMT

This project contributes to ZMT's mission by proposing a novel way to collect data in the field, which can be standardized across regions, which will allow to gather novel data previously unavailable. It will constitute a relatively low-cost package of monitoring devices that shall enrich the monitoring capability and inform management in coastal areas, while reducing human interference and health risks (e.g. diving accidents).

The proposed toolbox could stand out as a key ZMT product: as a technical transdisciplinary approach that serves to address societal challenges, it reflects perfectly the ZMT brand. The approach is a novel product that ZMT, owning the instruments and mastering the technical and logistic know-how, will be able to deploy in coastal areas worldwide through collaborative projects, providing a unique and direly needed service to our partners in tropical areas.

The fieldwork also provided occasions for promoting some of the values of ZMT and exercising its mission of capacity building and outreach by sharing our experience and knowledge with the local stakeholders, which was highly appreciated (Figure 26).

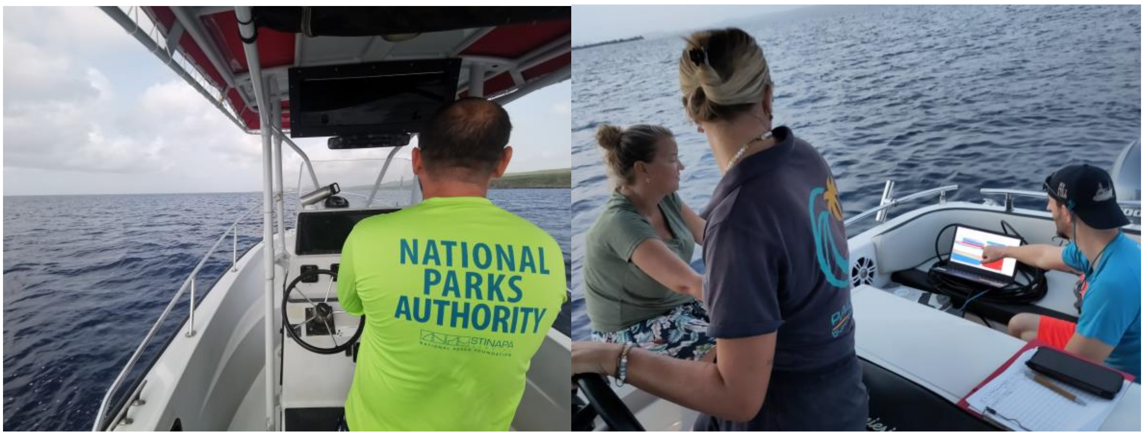

Figure 26. G. Romagnoni and T. Dudeck onboard with a STINAPA ranger (left) and explaining the scientific tools to Palm Boats staff (right). Licensed under CC BY-SA 4.0.

Next steps and follow-up

The IMFACT project was a self-standing project aimed at testing the usefulness of the proposed approach, with the intention of serving as a springboard for further projects, being research projects, scientific monitoring campaigns, or others. In this sense, during the entire project, ideas for follow-ups have been at the centre of our attention. Multiple ideas for application in Bonaire have emerged during discussion with STINAPA, or for applications in other contexts in tropical marine systems or others.

Here we mention a few:

- No diving was possible, and this compromised the possibility to investigate the bias caused by diving. A specific project would be needed to evaluate this aspect, which may take place in Bonaire itself or in other areas.
- In this framework, STINAPA have interest in comparison for conservation and fishery e.g. compare with visual census. A holistic visual census is carried out every 2 years using multiple snorkelers/divers along transects around Bonaire. STINAPA especially have expressed an interest in comparing this with our combined approach since these visual censi focus on the shallow reef area and would miss any pelagic fish.
- A whole- island pelagic (hydroacoustic) survey could be planned and performed to provide a quantification of the stock of barracuda, which is a key commercial species and the stock of which is currently not assessed. The local fishery authority could be contacted to propose such survey.
- Stakeholders (in particular STINAPA) expressed an interest in using the ROV for monitoring deeper water coral and sponges diversity and abundance. A plan for supporting such monitoring through the use of ROV dives to advance STINAPA's monitoring capacity could be proposed.
- The identification of species, or at least class, of the organisms composing the deep-water scattering layer by mean of a visual in-situ tool such as the ROV remains pending. This is an interesting scientific and technical question that could be the focus of a specific project.

- A larger scientific project could focus on comparing different systems to assess the robustness of the findings across shallow and deep reefs in productive (Bonaire) and less productive (e.g. Bahamas) systems
- Application of the ROV for measuring fish abundance in mangroves could be tested though comparing the applicability across mangrove systems (e.g. across Caribbean sites).
- Application for evaluating fish abundance in monitored areas could be a useful application well beyond the tropics, and in different areas including in European seas as well as lakes. This could for example be useful in studies monitoring the effects of habitat degradation (e.g. before-after underwater constructions) or habitat restoration (e.g. in areas were seaweed, corals, or rocky boulders are deployed to support marine life recovery), or in windfarms or other manmade structures, the installation of which may require environmental impact assessments.

Outside longer term plans, the next steps of more immediate interest include:

- Continuing with analyses
- Dissemination of the projects outcomes, possibly with availability of videos on a platform for communication.

Conclusion

The concentrated but extensive and thoroughly planned fieldwork allowed to concretely evaluate the pros and cons of the individual gears and of the combination of the tools, and to outline a perspective of applicability and of future steps for potential improvements. The combined toolbox was indeed effective in monitoring fish acoustically and visually at various depths; while caveats and bias have been identified, it emerges clearly that the proposed approach may be highly suitable for monitoring fish abundance, biomass and behaviour in coastal and pelagic areas. The tools were able to detect mobile species including small and large demersal and pelagic fish, which are key resources for small-scale fisheries. Our toolbox could thus enable MPA managers and scientists to improve accuracy in the estimation of fish abundance and biodiversity, ultimately facilitating sustainable fisheries management.

Acknowledgements

We gratefully acknowledge STINAPA for the support and collaboration before and during the fieldwork. We credit part of the success of this project to the boat and the help and expertise of Palm Boats staff.

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Appendix: synthesis of the IMFACT protocol

The project was set up including different types of surveys, some of which specifically designed to address a given questions, while others were structured so to be combined in order to be able to respond to multiple questions.

The IMFACT Protocol for data collection (available in a separate document) outlines all details, however a general overview is provided here. The survey types were originally designed before being on the field, with the precise intent to be adapted and modified along the way based on the practical experience gathered during the pilot project. Some suggested changes are reported here and further discussed in the section

Summary of findings.

Sample type 1 was designed in order to quantify the bias of the ROV and of snorkeling-based visual census. This was proposed as substitute of the diving-based visual census. Serial surveys at depth which allowed snorkeler's to count efficiently were planned (i.e. 5 meters depth).

The survey was based on the idea of counting fish in the same place with the three different methods (snorkeling, hydroacoustic, ROV). Originally the plan was to count key very visible species (barracuda or tarpon) but this was not possible, so reef fish were preferred instead. The snorkeler's ability to count fish was not properly assessed beforehand, and it was difficult to count fish in a straightforward way accounting for area limit (i.e. only 2 meters on each side of the transect). The high density of fish in shallow area made the exercise difficult. Focusing only on one target species or group (e.g. parrotfish) made the work easier, and more directly comparable at least with the ROV runs, although arguably missing on the use of the hydroacoustic array as a ground truth. Keeping a straight transect was not easy either. Measuring transect length of 25 m as proposed was not easy: instead, conspicuous reference points (two buoys) were chosen and transects run approximately in this stretch of length. In terms of measuring the snorkeler's bias this was probably not very easy and the results may not be representative. In terms of measuring the bias of the ROV, perhaps the more structured survey types (e.g. type 2) and the capacity of the hydroacoustic to directly observe the ROV and the escape effect that fish around it produce may be a better metric.

Survey type 2 was designed on the one side to measure the ROV's bias in counting fish at different depth (i.e. to verify if the bias varies with depth); on the other side it was designed to quantify changes with depth in abundance, biomass and biodiversity, and verify the feasibility to use either of the two tools for such use. It includes contemporary surveys with ROV and hydroacoustic being run contemporarily at three depth layers. The survey can then be repeated in various areas, including inside outside the MPA, for comparison.

Originally designed to be run at 10, 20 and 30 m depth, the survey proved more effective to be run at 5, 10 and 20 depth. However, especially for the hydroacoustic the depth maintenance was extremely difficult because of the topography of the sea bottom and in the case of steep slopes the depth would rapidly change. Maintaining a depth range (e.g. between 5 and 10 m, between 8 and 12 etc.) was feasible in some, but not in all cases. Transects that continuously shift from 5 to 40 m depth in the space of few meters or similar were common. A "putative" target depth layer was often declared. This allowed to evaluate the data and compare them by transect for a given "putative" depth layer. This problem was not as severe with the ROV which can better manouver the depth to maintain the depth layer. However, when doing so the ROV was often changing route, with the result of having a more convolute path and sometimes not being able to follow the boat. The capacity to follow the ROV direction with the boat was only conquered with experience. For the future, the focus should be on following the ROV as done in the last few days of the fieldwork.

Survey type 3 was designed to test the ROV's capability to execute surveys at greater depth (up to 100 m as per specification of the constructor), and to check the bias if possible, and the hydroacoustic capacity to monitor at greater depth. This survey included ROV explorations at pre-established depths, with transects planned of 1 minute length.

The main issue with these transects was the capability to run them in a systematic way, considering the drift could carry away the ROV off the boat, making it impossible to follow the ROV with the hydroacoustic. This was not the plan anyway. Another issue was the battery life which limited deep dives number and duration. The pre-decision on dives depth was not clear and rather depended on the underwater situation. Layers at depth show in some cases difficult counting per depth in e.g. vertical walls which make it hard to decide on what depth to follow. As compared to gently declining slopes. The survey included a longer transect to check if by increasing length one reaches a plateau of e.g. species richness, but this was not performed systematically.

Survey type 4 was aimed at collecting information on the pelagic species, both small and large ones. The intent was to either aiming for schools in known plausible locations, or using this as "ad-hoc" method to be used during transfers, to then use the ROV for identification of the species of the observed fish schools or individual pelagic fish.

Ultimately, the transfers were not suitable because the boat had to slow down when the hydroacoustic was in the water, so that proper transfers required high speed and the hydroacoustic was in these cases lifted from the water. The system proved very effective and allowed identifications of species and schools although it required circulating and returing on the area several times. It was suitable for stationary species.

Survey type 5 was a night time version of sample 2. This survey was not performed with ROV in practice, but only with hydroacoustic. The ROV was, at the time of testing, not charged enough and the weather conditions did not allow to test it in practice, and the attempts to trial test it resulted in the cable rapidly entangling itself and in the visibility being null because of the abundance of plankton.

Survey type 6 included transects to observe migration, parallel or perpendicular to coastline, with hydroacoustic, and then test with the ROV what species was observed to be migrating toward the surface. While the measuring of the hydroacoustic was practical, the identification of the species with the ROV was not in practice feasible: the depth was too large to be reachable. In addition, the deployment with lights on resulted in the ROV to be immersed in plankton attracted by the ligh, impeding any visibility.

Survey type 7 was planned to be an experiment to test for the disturbance of ROV light either at night or depth. This was feasible in particular with depth and during day, because night dives were not very successful with the ROV.

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