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# Pulse beam trawling vs. traditional beam trawling in German shrimp fishery: a comparative study


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**Master thesis**

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# List of Abbreviations

| | |
|---|---|
| AC | Alternating current |
| ASH | A-shrimp |
| BSH | B-shrimp |
| BYC | By-catch |
| calc | Calculated |
| CPUE | Catch per Unit Effort [l/h] |
| CTD | Conductivity, temperature, depth |
| DC | Direct current |
| declin | Declination |
| EC | European Council |
| Eot | Equation of time |
| $H_0$ | Null-Hypothesis |
| HOVERCRAN | HOVering Pulse Trawl for a Selective CRANgon Fishery |
| lat | Latitude |
| long | Longitude |
| m | Weight [kg] |
| max | Maximum |
| med | Median |
| min | Minimum |
| No. | Number |
| PT | Pulse trawl |
| SA | Solar altitude |
| ShA | Solar hour Angle |
| ST | Standard trawl |
| TOS | Total shrimp fraction |
| TOT | Total catch |
| UND | Undersized shrimp fraction |
| V | Volume [L] |

# 1 Introduction

## 1.1 Background on *Crangon* fishery

One of the many regional specialties from the German North Sea coast are brown shrimp (*Crangon crangon*, Linnaeus, 1758; Figure 1), a benthic species, usually half- buried in the sand, scavenging on any food source (STADIE, 2001; KUIPERS & DAPPER, 1981). Just recently, *Crangon crangon* has been regarded as a delicacy by gourmet chef Björn Freitag in a German TV program (MUDERSBACH & DIRKS, 2012).

**Figure 1: *Crangon crangon* (© vTI-OSF)**

The demand of *Crangon crangon* is met by around 600 vessels along the European North Sea coast of which approximately 220 operate under German flag (ULLEWEIT *et al.*, 2008). In 2010, these ships landed 13,476t of *Crangon crangon* providing almost 40% of the total landings along the European North Sea coast. The German *Crangon*-landings were only exceeded by the Netherlands, where 16,684t were landed in 2010 (ICES WGCRAN, 2011). Traditionally, the *Crangon* fishery is seasonal with high landings in the fall and low landings in the winter months (AVIAT *et al.*, 2011).

For over 100 years, beam trawling has been the standard fishing method for *Crangon crangon* along the North Sea coast (VORBERG, 1997), however the industrialization of the fleet did not take place until the 1950s (AVIAT *et al.*, 2011). A - so-called - bobbin rope is dragged over the ground, startling the shrimp which are caught by the following net. Beam trawling has been heavily criticized, due to its low selectivity and heavy gear (GREENPEACE, 2012; RÖSNER, 2009), even though the shrimp-gear is much lighter compared to the beam trawl used for sole-fishing. The mesh size in the *Crangon* fishery is very small, as the target species *Crangon crangon* grows to only about 9cm in length (CATCHPOLE *et al.*, 2008). By law, the stretched mesh size may not be smaller than 16mm in the codend (WESSENDORF, 2010). As a result, a fair amount of small fish is caught as unwanted by-catch. Thus, most of the by-catch consists of crabs and juvenile flatfish. The issue herein lies in the fact, that the German fishing grounds for *C. crangon* are mainly located in the Wadden Sea, an important ecosystem, National Park and UNESCO World Heritage (UNESCO, 2010). The Wadden Sea, also called the "nursery area" for many fish species (FEHMEL, 2008), provides a heritage for many juvenile fish, especially plaice. The importance of the Wadden Sea for plaice recruitment has been acknowledged by the European Union by regulating the fishery in the "plaice box". The "plaice box" is an area along the coast of the south-eastern North Sea (BEARE *et al.*, 2010). Vessels with engine powers of more than 221kW are not allowed to fish in this area according to Council Regulation (EC) No 3094/86.

The restriction on engine power in a certain area is, along with the limit in mesh size one, of the few regulations applied to *Crangon* fishery in an attempt to make it more sustainable. Another measure to reduce unwanted by-catch is the mandatory use of sieve nets (Council Regulation (EC) No 850/98) for the main part of the fishing season. The sieve nets allow larger fish to escape after entering the net. Further possible devices to improve species selectivity are sorting grids installed in front of the codend. An overview of various types of sorting grids also in combination with large mesh panels and their effectiveness is given in BROADHURST (2000). Additional progress has also been made in the sorting process on board. The original shaking sieve to sort commercial shrimp from by-catch was replaced by a more fish-friendly device (DE JONGE *et al.*, 1993), the rotary sieve. This device has a higher sorting efficiency leading to a higher survival rate of by-catch species (BERGHAHN *et al.*, 1992).

All of these measures aim at a reduction of by-catch mortality once the unwanted species have entered the net. Despite high survival rates after being directly washed back into the water, these fish are exposed to stress and potential damage in the fishing and sorting process. Stress has been named one of the major factors of fish mortality (KELLE, 1977). The prevention of stress-induced mortality would be possible if the selection process took place before unwanted by-catch entered the net. This can be achieved by creating a stimulus in the net mouth only affecting the target species *Crangon crangon*, without disturbing animals sharing their habitat (POLET *et al.*, 2005a). The current stimulus in beam trawling is the water turbulence, created by the bobbin rope (BERGHAHN *et al.*, 1995). This unspecific turbulence stimulates shrimp, as well as other species. The search for an alternative stimulus led to the idea of using electric fields to startle shrimp.

## 1.2 Applications of pulse fishing

The application of electricity in fisheries has a long history. Patents for electrical fishing gears go back to 1863 in Britain (VIBERT, 1967). Electrical fishing was first used in fresh water and is mainly applied in fresh water until today. The limits of electrical fishing in sea water lie in the conductivity of the water. Sea water has a much higher conductivity than fresh water leading to a higher necessary power input in order to achieve the same strength of the electrical field. In order to save power it is suggested to use short direct pulses in sea water (HALSBAND, 1967). Electrical fishery in European waters was introduced in the following fisheries during the past years: *Ensis spp.* fishery in Scotland, flatfish fishery and shrimp fishery.

### 1.2.1 *Ensis spp.* fishery in Scotland

The recently reported electrical *Ensis* fishery in Scotland is an example for electrical fishing in sea water without pulses. Since it is an illegal fishery, the information on currently used gears is anecdotal (ICES SGELECTRA, 2012). The most common method of electrical fishing seems to be the application of a welding generator up to 100kW AC as the power source. Divers usually follow the electric gear and hand pick *Ensis* that have left their burrow (ICES SGELECTRA, 2012). SEAFISH, a British non-Departmental Public Body active in the seafood industry, made a report on a self-built electrical device used in *Ensis* fishery (WOOLMER *et al.*, 2011). The gear consisted of 3 electrodes at a distance of 0.6m and supplied with 24V DC from a welding generator resulting in electrical field strength of 40V/m. Underwater observation revealed that unwanted species such as fish and molluscs mainly showed avoidance of the gear or disorientation, once in contact with the electrical field. The animals have shown a short recovery period. It was concluded, that electrical fishing with low voltage and amperage could be an effective option for harvesting *Ensis* (WOOLMER *et al.*, 2011). A concern of unregulated electrical fishing for *Ensis* is the possibility that chlorine is formed at high electrical power levels. Since the gear is very slowly dragged over the sea bed this electrolytic reaction is possible (ICES SGELECTRA, 2012). Further investigations and follow-up on this fishery is recommended by SGELECTRA.

### 1.2.2 Flatfish fishery

One of the first applications of electrical fishing in sea water was in the flatfish fishery. The driving motive for a development of an electrical stimulus was the reduction of fuel consumption (VAN MARLEN *et al.*, 2006). Various prototypes have been developed since the 1960s, especially in the Netherlands, but there has not been an application to the commercial fishery (VAN MARLEN *et al.*, 2007). Especially at IMARES (Netherlands) a lot of research on flatfish-pulse-fishing has been carried out since the late 1990s (ICES SGELECTRA, 2012). The experiments on a variety of vessels with different configurations have generally shown promising results in the catch efficiency of plaice and sole, in the reduction of undersized sole and higher survival rates for undersized plaice (VAN MARLEN *et al.*, 2007). In the two latest studies in 2006 and 2011, a pulse trawl system was installed on commercial vessels with a 12m beam. The first study compared two fishing vessels fishing in parallel, one with the standard equipment and one with a pulse trawl equipment developed by the company *Verburg-Holland Ltd*. The results showed lower landings of sole and plaice, and no difference in the catch rates of undersized sole and plaice. However, less benthic fauna was caught using the pulse gear. In accordance with previous research, there was an indication that undersized sole and plaice showed a higher survival rate when caught with the pulse gear (VAN MARLEN *et al.*, 2006). A significant reduction in fuel consumption was recorded.

The most recent study, conducted in 2011 (VAN MARLEN *et al.*, 2011), compared different settings of voltage, frequency, pulse duration and power input with a control vessel using tickler chains. The pulse gears were installed on two different vessels (TX36 and TX68), comparing three vessels in total. The pulse characteristics are shown in Table 1.

**Table 1: pulse characteristics of pulse gears compared in VAN MARLEN *et al.* (2011). Two vessels (TX36, TX68) are compared to a standard flatfish trawler with tickler chains**

| | TX36 | TX68 |
|---|---|---|
| Voltage | 45V | 50V |
| Frequency | 45Hz | 50Hz |
| Pulse duration | 0.38ms | 0.22ms |
| Power input (one gear) | 7kW | 8.5kW |

Overall, a catch reduction of target species of 65% - 69% was observed. Simultaneously, the number of undersized fish was also reduced by 30% - 50%. Furthermore, less benthic species were caught using the pulse gears. Very few animals brought on board showed spinal injuries during these trials, however no information is available on animals that escaped the trawl.

The report stated that the technical requirements and restrictions on such pulse gears are currently discussed. Prior to an introduction of pulse trawling for flatfish, the settings of restrictions have to be decided upon.

### 1.2.3 Shrimp fishery

As the Netherlands have been one of the leading nations in *Crangon* fisheries (ICES WGCRAN, 2011), it is only natural that scientists in this country have played a leading role in the development of new ways of stimulating shrimp (WOOLMER *et al.*, 2011) in order to increase efficiency. Work on one of the first electrified beam trawls in the Netherlands was published by BOONSTRA & DE GROOT (1974). In this study, frequencies between 5Hz - 50Hz, a pulse length of 0.55ms and output voltage of 10V were in use. Very promising results were recorded with a higher catch rate for commercial shrimp. Due to a ban on electrical fishing in sea water in the European Union, most researched ceased in the 1980s (POLET *et al.*, 2005a). However, it has been reported that pulse fishing for shrimp was also investigated and applied in Chinese waters during the 1990s (YU *et al.*, 2007). The pulse parameters of the recommended apparatus were similar to the settings used in the Netherlands. It became practice to increase the power output of the recommended gear and increase the strength of the electrical field. As a result, more juvenile shrimp were caught. Since there were no regulations on the pulse parameters, many gears were manufactured with characteristics exceeding the sustainable recommendations. This led to serious overfishing of the population by the more than 2000 vessels and the ban of pulse fishing in 2001 (YU *et al.*, 2007).

Another outcome of the electrical fishing in Chinese waters at that time was the initiation of the HOVERCRAN research in Belgium as “a Belgian fishing vessel owner (…) brought a Chinese pulse generator back to Belgium” (POLET *et al.*, 2005a). The aim was to reduce by-catch by removing the bobbin rope and substitute the mechanical stimulation by the bobbins via a *Crangon*-specific electrical field. Laboratory experiments were carried out to define the threshold of pulse amplitude and frequency to startle *Crangon crangon* in any position relative to the electric field. Since the electric field is not homogenous, the animals are subject to a variety of possible pulse strengths. It was found that field strength of 24V/m is the threshold for any size of shrimp in any position to be startled. The application of the pulse on common by-catch species resulted in harmless swimming reactions of sole and dab, but no reactions were shown from, e.g. plaice, rockling and dragonet. After the laboratory experiments, the gear was tested at sea (POLET *et al.*, 2005b). The sea trials in Belgian waters showed almost equal catch volumes of shrimp and the confirmation that by-catch species escape underneath the ground rope when the bobbins are removed. After the development of the HOVERCRAN-system, the gear was installed on three Dutch vessels, where currently catch comparisons are carried out (ICES SGELECTRA, 2012). Additionally, a project was initiated in Germany to obtain detailed information in direct catch comparisons. This study was conducted within this project.

## 1.3 Task and hypotheses

The performance of a *Crangon*-pulse trawling system under commercial conditions in German waters was evaluated. These conditions were ensured by installing the HOVERCRAN-system with a modified bobbin rope on the commercial *Crangon* vessel SD33 “Marlies”, which fishes in the coastal area of Büsum, Germany.

On starboard the new gear was installed, while on portside the standard gear was used. This allowed a direct comparison of the catches under commercial conditions. The majority of data was collected via self-sampling conducted by the crew of the vessel, who documented the volume of a variety of catch fractions for every haul: total catch, commercial shrimp fraction, by-catch, A-shrimp and B-shrimp. Due to the commercial conditions, the hauls covered a 24h-period. The self-sampling was accompanied by regular attendance of a scientist during the trips.

The self-sampling was complemented with a phase of scientific-sampling, where a group of scientists were on board the vessel collecting more detailed information about the catch and evaluating the influence of towing speed and salinity, as well as the performance of the pulse gear without the activity of the pulses.

This thesis covers the first phase of a 12-months-project, where the major part of data is obtained via self-sampling Ten days of scientific-sampling were also included, allowing a more thorough evaluation of the by-catch. The two main hypotheses in this study are:

1. The electric field between the electrodes substitutes the bobbins as a stimulus for startling shrimp and thus there is no loss in shrimp catches.
2. The reduced number of bobbins in the modified bobbin rope opens an escape route for unwanted fish and thus less by-catch is produced using the pulse gear.

# 2 Materials and Methods

## 2.1 The vessel

In order to ensure commercial conditions during the experiments, the commercial shrimp vessel SD33 “Marlies” was equipped with the pulse beam trawl system. The vessel is owned by a local fisherman and operated by himself and one assistant on deck. It is usually in use in the German Wadden Sea region, often fairly close to shore (Figure 12). According to the fisherman, the vessel travels as far as to the west of the island of Helgoland during the winter months to fish. Figure 2 shows the vessel and an overview of its properties can be seen in Table 2.


**Figure 2: Fishing vessel SD33 “Marlies” in the port of Büsum, Germany**

**Table 2: Properties of SD33 "Marlies"**

| | |
|---|---|
| Vessel type | *Crangon* trawler |
| Length | 17.25m |
| Width | 5.30m |
| Draft | 2.15m |
| Engine power | 221kW |
| Horsepower | 300PS |
| Year of construction | 1973 |
| Port of registry | Friedrichskoog |
| Call sign | DSQD |
| Beam length | 8.40m |

The installation of the new system took place between June 11, 2012 and June 15, 2012. The data collection started after a short period of familiarization on June 20, 2012.

During regular fishing operation, the fisherman and his deck hand collected data via self-sampling (Chapter 3.2). The self-sampling phase was accompanied by regular attendance on board during the trips. In addition to the self-sampling, a group of four scientists was on board between August 13, 2012 and August 24, 2012. This period is referred to as "scientific-sampling" (Chapter 3.3). Additional data, such as species composition and length distribution of by-catch species were collected during this period. The data analyzed in this study were collected between June 20, 2012 and August 24, 2012.

## 2.2 The pulse trawl system

The pulse trawl system, installed on board, is made up of two parts: one is the modified beam trawl and the second part is the actual gear providing the pulses. The latter is known as HOVERCRAN (**HOV**ering Pulse Trawl for a Selective **CRAN**gon Fishery) and built by the Belgian company *MARELEC NV*.

### 2.2.1 The modified bobbin rope

The basic idea of the HOVERCRAN is to substitute the standard bobbin rope with lightweight electrodes. Like this, the former mechanical way of startling shrimp is replaced by a *Crangon*-specific electric pulse. In the original design, which was first used in Belgian waters, the bobbins were entirely abandoned and the ground rope raised in such a manner that non-target species could escape underneath (Figure 3).

**(A)** **(B)**

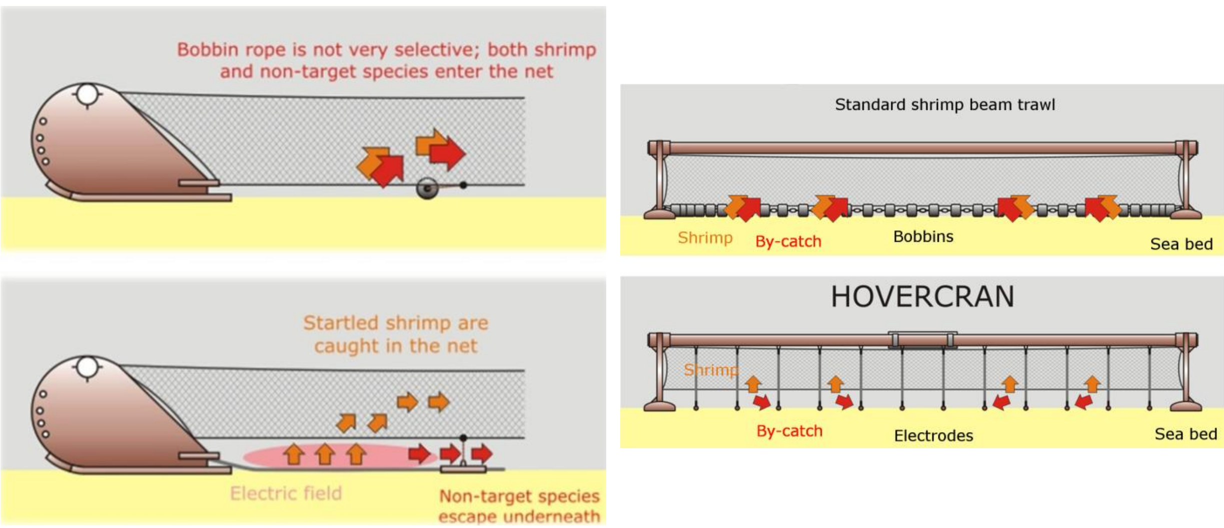



**Figure 3: Comparison of the original shrimp beam trawl with standard bobbin rope (upper figures) and HOVERCRAN-pulse trawl with raised bobbin rope (lower figures). (A) side view, (B), front view. The non-target species are able to escape underneath while the shrimp are startled and caught in the net. (adapted from VERSCHUEREN & POLET (2009), permission granted)**

Due to the structured and unstable surface of the sea bottom in the German Wadden Sea (STADIE, 2001), where the experiments took place, the fisherman was concerned about eliminating all bobbins. As a compromise, a rope with fewer bobbins was installed. The larger distance between the bobbins preserved the idea behind the HOVERCRAN - to let non-target species escape underneath the net - well enough. Due to the fact that all electrodes are of the same length, a design with a straight bobbin rope was developed. The design was adapted from previous Belgian trials. The adaptation of the net was done by the fisherman. The bobbin rope in use can be seen as a schematic drawing in Figure 4 and in actual use in Figure 5.

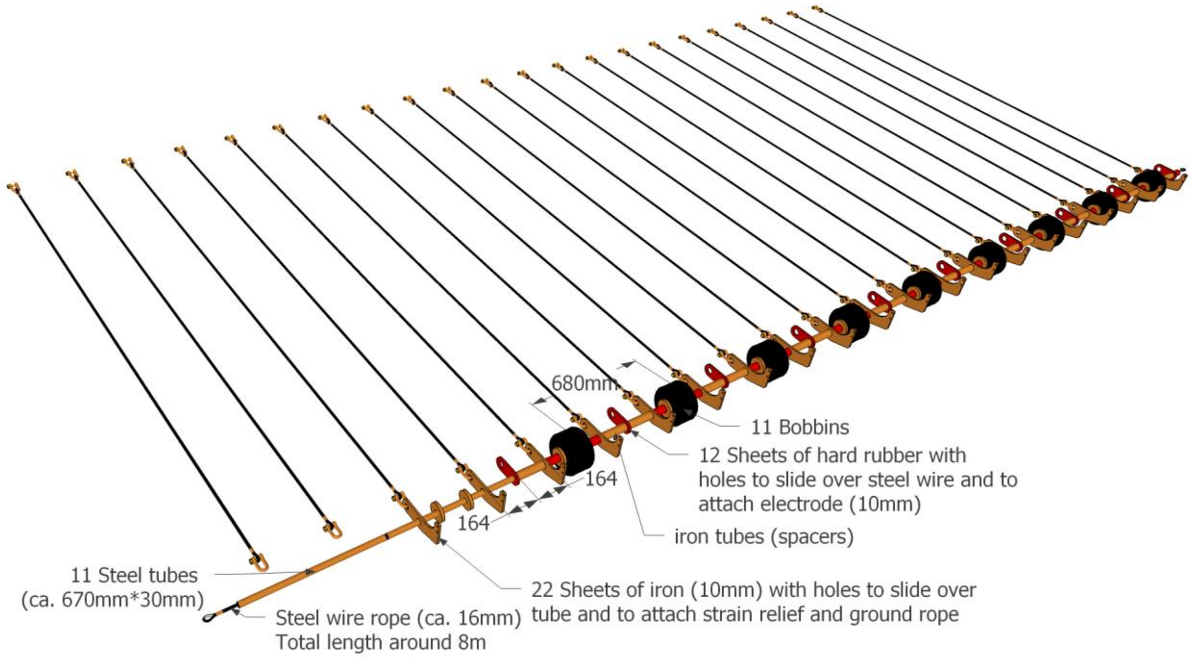



**Figure 4: Schematic drawing of the straight bobbin rope (adapted from VERSCHUEREN, personal communication, 2012)**

The core of the bobbin rope is a 16mm steel wire. In a first trial, the spacers were made of hard plastic, but the material did not prove to be durable enough to. They were replaced by spacers made of steel. The connection between the bobbin rope and the ground rope can be set at two distances. For the trials analyzed in this thesis, the ground rope was set to the smallest possible distance to the bobbins.

**(A)** **(B)**

**Figure 5: Gears used during the sea trials. (A) standard beam trawl with U-shaped bobbin rope on portside (beam prepared for electrodes) (B) HOVERCRAN-pulse gear with straight bobbin rope on starboard**

### 2.2.2 The pulse gear

The main element of the HOVERCRAN system is the pulse generator on the beam. It converts conventional alternating current (230V, 50Hz) supplied from the ship to direct current pulses (4.5Hz, 0.25ms) which run to the electrodes. Between the electrodes a pulsed electrical field with approximately 30V/m is formed. A supply cable runs from the ship's generator to a control cabinet and is then led to the beam via an automatic winch for each side. The supply cable is lowered and hauled automatically, as the unit is designed to hold constant tension on the cable. When using the standard equipment, the beam rotates on its own axis; in order to prevent this, the HOVERCRAN beam was made immobile by fixing it to the trawl head, using a slot and tongue-design. Since little or no tension should be applied to the electrodes, strain relieves were attached between the beam and the bobbin rope. All parts are made of stainless steel and are therefore resistant against sea water. The electrodes consist of a threaded stainless steel cable where one strand is replaced by a copper conductor. The twelve electrodes always work in pairs, so that there are eleven pairs in total. Each pair is alternatively fed by the pulse generator, thus the electric field runs across the beam from the first pair to the last and restarts the cycle. By feeding only one pair of electrodes at a time electrical energy is saved. Power is automatically switched on to the HOVERCRAN-system as soon as more than 10m of wire are unspooled. This also enhances safety of the crew onboard. All parts were built and installed by *MARELEC NV*. Figure 6 shows the set-up in detail and the overall final design is depicted in Figure 7.

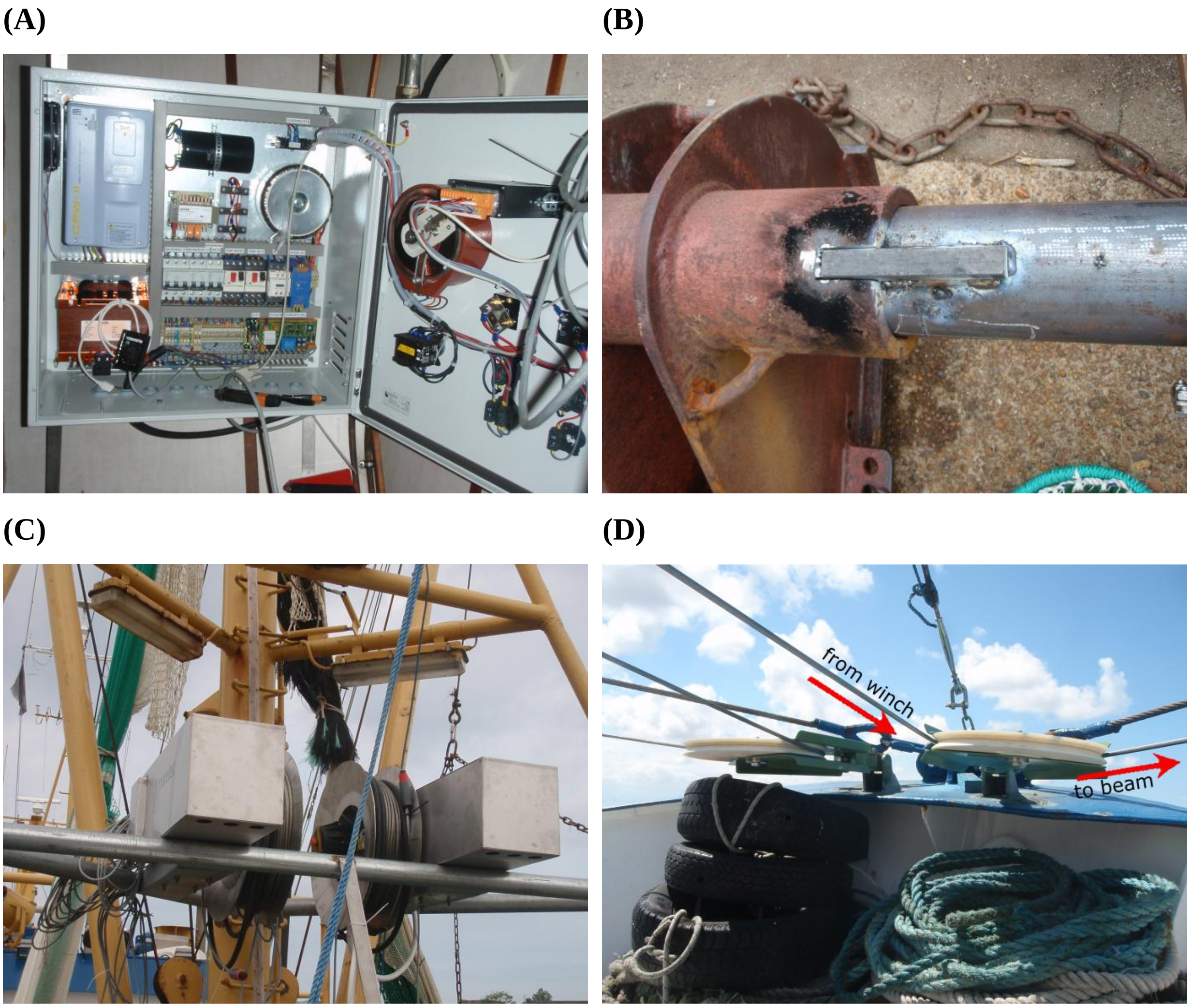



**Figure 6: Details of the HOVERCRAN-system. (A) control cabinet (B) attachment of pulse beam to trawl head (C) automatic winches with engines (D) pulley block at the bow of the vessel guiding the supply cable from the winches to the beam**

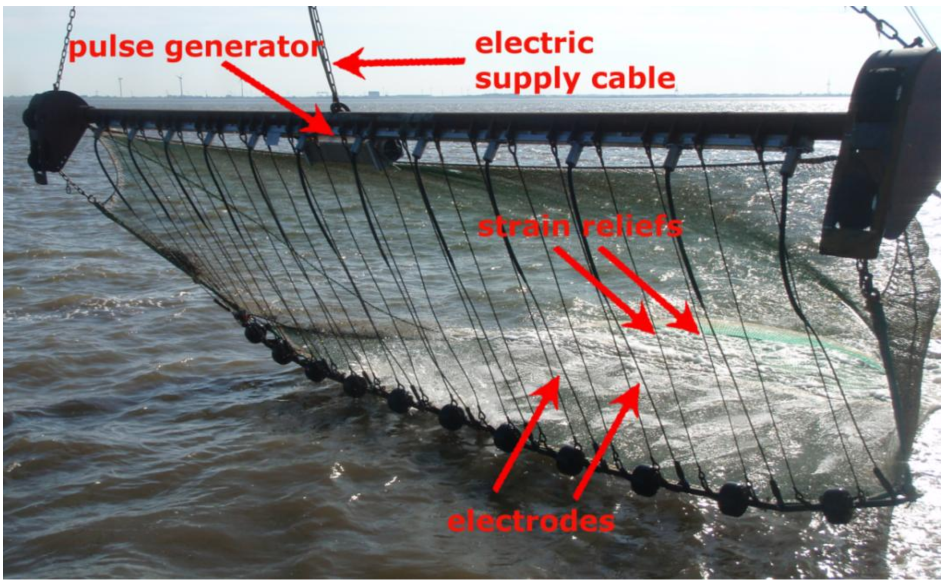



**Figure 7: A pulse trawl, equipped with HOVERCRAN-system, as installed on SD33 with a straight bobbin rope, 12 electrodes, strain reliefs and pulse generator on the beam.**

## 2.3 Data collection

The major part of the data were collected via self-sampling by the crew on the vessel. This period was monitored by regular attendance at the trips. A team of scientists joined the work on board for a short period. This period will be referred to as scientific-sampling phase. During this time, the collection of data was extended.

The experimental set-up of this study provided a direct catch comparison of the standard gear and the pulse gear. This required separate catch processing and the quantification of all catch fractions. In order to measure and process one catch after another, the hopper where the catch was emptied into, once the net was on board, was divided into two parts, prior to the start of the data collection.

The total catch volume was calculated using the height of the catch in these hoppers. As a result, a relation between height of the total catch and its volume had to be established experimentally, prior to the data collection. This relation was determined by emptying a known volume of water into the hopper and measuring the according height. One data point was marked every 10L. The volumetric measurement was done for the lower part of the hopper, as it is irregularly shaped. A non-linear model, based on the assumption in Equation 1, was applied to the height measurement for this lower part. During the gauging of the hopper, the volume was the known variable. Hence, the height had to be calculated. Once this relation was established, the equation was solved for the volume (Equation 2) and thus, the height could be used for the computation of the volume.

$$Height_{lower\ part\ of\ basin} = a * Volume^2 + b * Volume + c$$ **Equation 1**

$$Volume_{lower\ part} = \frac{b}{2a} + \sqrt{\left(\frac{b}{2a}\right)^2 - \frac{c - Height}{a}}$$ **Equation 2**

where $a$, $b$ and $c$ are factors that were calculated once the model was applied to the actual data. The upper part of the hopper is a regular square which made it possible to establish the relationship between volume and height without an experiment.

Several baskets normally used on fishing vessels were subject to volumetric calibration and were then used to measure the volumes of the individual fractions. Since all baskets are identical, the height-volume-relation was only established for a single basket and the measurement transferred to the others. The baskets were marked in steps of 5L.

Once the nets were on board, the catch was processed as described below. An overview of all fractions in given in Figure 8. The sampling protocol is valid for both the self-sampling and the scientific-sampling, if not else specified.

1. Codends are opened and catches are emptied into the hoppers.
2. Height of total catch is determined.
3. First hopper is opened and catch is released onto a conveyor belt leading to a rotary sieve.
4. Rotary sieve divides catch into:
    - Commercial shrimp fraction
    - By-catch
    - Undersized shrimp
5. Handling of by-catch
    5a Volume of by-catch is determined
    5b. Weight of by-catch is determined (scientific-sampling only).
    5c. By-catch is sorted by fish species and analyzed (scientific-sampling only).
6. Handling of commercial shrimp.
    6a. Volume of commercial shrimp is determined.
    6b. Weight of the commercial shrimp fraction is determined (scientific-sampling).
    6c. Sub-sample from the commercial shrimp fraction is taken and fish in this fraction are sorted out (scientific-sampling only).
7. Volume and weight of undersized shrimp are determined (scientific-sampling only).
8. Commercial shrimp fraction is cooked.
9. Shaking sieve divides cooked shrimp into:
    - A-shrimp (large, marketable)
    - B-shrimp (small, marketable)
    - Discard: C-shrimp (undersized), smallest fish
10. Volume of the two marketable sized shrimp fractions is determined.
11. Both fractions are stored in a cooled room on board.
12. Steps 3. – 11. are repeated for the second hopper.

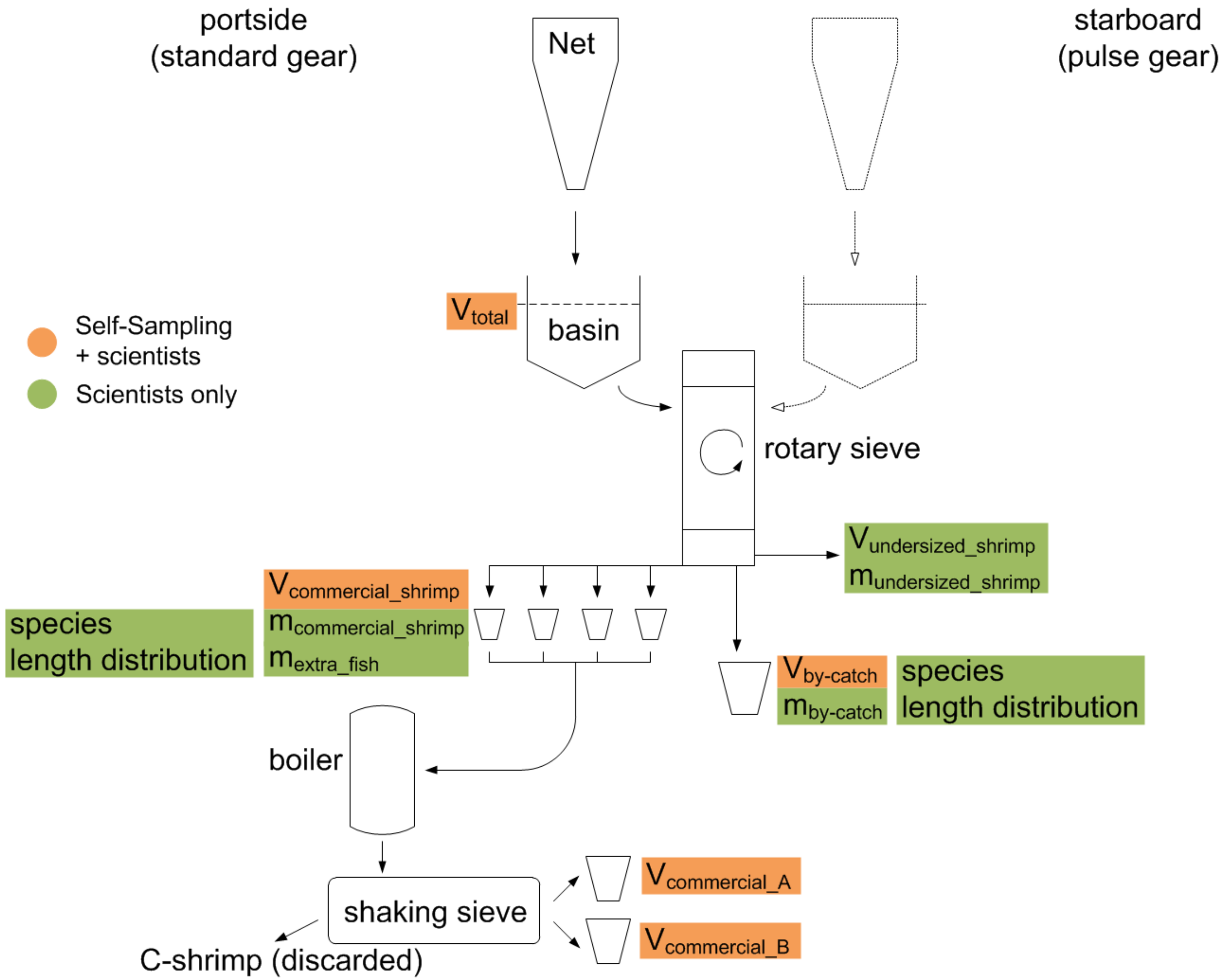



**Figure 8: Overview of the fractions measured. The colors mark the sampling phases during which the fractions were measured: self-samping & scientific-sampling (orange); scientific-sampling only (green)**

The weight of the different catch fractions was measured using a hanging scale Model KERN HCN 50K100IP for large quantities (up to 50kg, resolution: 0.1kg) and a hanging scale Model KERN HDB 10K10N (up to 10kg, resolution: 0.01kg) for medium sized quantities. The two scales were in use, as the weight of the fractions varied from haul to haul. It was attempted to measure the weight at the highest possible resolution. The very low weights of individual fish were measured using a common kitchen scale. Due to bad weather conditions resulting in high swells, the weight of small amounts of fish could not always be determined, as the scales are not designed for strong movement.

As a result of their shape and size, some fish are not sorted out in the rotary sieve but pass on through to the commercial shrimp fraction. It was impossible to separate those fish during self-sampling. When the scientists were onboard, it was aimed to also sort the shrimp fraction. In those cases an additional “extra-fish”-fraction was measured. A sub-sample from the commercial shrimp fraction was taken in order to estimate the amount as well as species and size composition of fish within. Sub-sampling was also applied when evaluating species and size distribution in the fraction “by-catch”. The entire by-catch fraction was searched for species not sufficiently represented in the sub-sample. These fish were measured as well. The length distribution of species was determined at least once a day, weight and number of individuals was usually taken for every haul.

The shaking sieve on board consists of two grids. The upper grid, with 9mm distance between the metal bars, separates large, marketable shrimp (A-shrimp) from the rest of the fraction. The lower sieve with 6.2mm space between the bars separates small, marketable shrimp (B-shrimp) from non-marketable shrimp (C-shrimp) and smallest fish. The C-shrimp are undersized shrimp not sorted out in the rotary sieve. They are discarded immediately and the volume could not be determined directly due to the set-up of the shaking sieve. However, by calculating the difference in volume before and after sorting, this fraction can be estimated. After sorting and determination of the volume the marketable shrimp are joined back together as it is only information for the fisherman and a set of data, and stored in a cooled room on board.

## 2.4 Non-biological data

In addition to the collection of biological data a series of other variables was collected. For each haul, the fisherman kept record of the following data in a bridge protocol: beginning and end of haul, start and end position of haul, ground conditions (sand or clay) and position of tideway in relation to the vessel.

Furthermore, two Star Oddi CTD loggers (Figure 9) were installed on the beams at the beginning of the trials. These loggers register date, time, temperature, depth and salinity at a 120s-interval. On the starboard beam, running the HOVERCRAN, a Star Oddi logger type "logic" was installed, which only switched on at a certain depth to save storage capacity and battery life. The other beam was equipped with a regular Star Oddi logger. The data were retrieved from the loggers at regular intervals.


**Figure 9: Star Oddi CTD logger and housing. The logger is inserted into the housing before being attached to the beam. The screw ensures that the logger does not fall out. A cable tie is also fastened for security.**

The logger type "logic" did not operate as intended due to an internal offset. The logger measured a depth shallower than the real value. In shallow waters (approximately <1.5m) the logger did not turn on at all.

Since the logger type "logic" did not register data at all given times, it was necessary to use the other logger as a reference. A small experiment was conducted to verify that the logger type "regular" was working properly. The logger was submerged to a known depth and this depth was compared to the measurements by the logger. The experiment revealed, that the regular logger also had an offset. The data fluctuated +20%/-10% around the set depth. According to the Star Oddi customer service the loggers operate with an accuracy of 0.4m, thus the depth can only be estimated in shallow regions. The comparatively poor accuracy made it impossible to precisely eliminate the offset. However, the Star Oddi logger type "regular" was used as a control unit for the bridge protocol, as beginning and end of submergence can be associated with the beginning respectively end of the haul.

In order to prevent misinterpretation and for redundancy, another source of data to validate beginning and end of a haul was used. The computer connected to the HOVERCRAN-system logs every time the current starts and stops flowing, thus showing beginning and end of the fishing activity. Furthermore, the voltage between each pair of electrodes is recorded.

A GPS logger Type Qstarz GPS Sports-Recorder BT-Q1300ST was used to record the ship position, speed and course made good. The logging interval was set to 60s. Due to technical problems the logger did not record at all times. The following intervals were covered: June 20 - 25, 2012; July 4 - 23, 2012; August 8 - 24, 2012, collecting data on 154 out of 192 hauls.

Ten meshes were measured in each codend according to the standard procedures (ICES, 2005), using an OMEGA mesh gauge to avoid an effect on catchability of *Crangon crangon* due to the mesh size in the codend.

## 2.5 Data analysis

In order to evaluate significant differences between the standard and the pulse gear, the statistical computing software R was used (R DEVELOPMENT CORE TEAM, 2012). All data sets were tested for normal distribution using the Kolmogorov–Smirnov test or the Shapiro-Wilk test if less than 50 samples were available (RAZALI & WAH, 2011; AHAD *et al.*, 2011). Variance homogeneity was tested by using Levene's test (CARROLL & SCHNEIDER, 1985; MARQUES DE SÁ, 2007). Significant differences between the systems were detected using the non-parametric Wilcoxon Sign Rank Test for paired samples, as the samples were not normally distributed (BÄRLOCHER, 2008; SACHS & HEDDERICH, 2006). The data sets were treated as paired samples when all parameters except the gears were the same (LOZÁN & KAUSCH, 2007) and the same population was fished simultaneously. Due to the nature of the test, only data sets with data collected for both standard gear and pulse gear can be evaluated. All significance tests were carried out as two-sided tests. The Null-Hypothesis for all comparisons is: $H_0$ = no significant difference between the two groups. As a result, a p-value below 0.05 indicates a significant difference. Additionally, a linear model was applied to the data and evaluated as well. Data quality and influence of single data points was assessed using the Cook's distance (COOK, 1977). Values with a Cook's distance greater than 1 were investigated further and removed from the evaluation and the plot if they were obviously caused by a faulty measurement or inaccurate protocolling. The Null-Hypothesis for the linear model is: $H_0$ = slope is equal to 1. A t-test was carried out to assess whether the slope differed significantly from 1. The confidence intervals of the linear regression were calculated using the `predict()` function in R.

The evaluation of the data comprises the comparison of absolute volumes and the Catch per Unit Effort (CPUE) in (l/h), as well as the evaluation of the share of the HOVERCRAN in the overall catch in every fraction. The calculation of the percentage was done using Eq. 3.

$$Volume\_Percentage_{pulse\ trawl} = \frac{Volume_{pulse\ trawl}}{Volume_{pulse\ trawl} + Volume_{standard\ trawl}} * 100 \quad \textbf{Eq. 3}$$

The categorization of the hauls into the different times of day (day, twilight, night), was done by calculating the solar altitude for beginning and end of a haul. The calculation was done based on the spreadsheet calculation tool provided by GIESEN (2001 – 2007). The input data needed are: latitude (lat), longitude (long), date (month, day) and time (hour, minute). The degree measure was converted into radian measure by the constant K. The process for calculating the solar altitude is given in Eq. 4– Eq. 10.

Constant
$$K = \frac{\pi}{180} \quad \textbf{Eq. 4}$$

Day number
$$N = month - 1(* 30.3) + day \quad \textbf{Eq. 5}$$

Part of year
$$n = K * \frac{(N - 1 + \frac{\left(hour + \frac{minute}{60}\right) - 12)}{24}}{365} \quad \textbf{Eq. 6}$$

Declination
$$declin = 0.006918 - 0.399912 * \cos(n) + 0.070257 * \sin(n) - 0.006758 * \cos(2 * n) \quad \textbf{Eq. 7}$$

Equation of time (Eot)
$$Eot = 229.18 * (0.000075 + 0.001868 * \cos(n) - 0.032077 * \sin(n) \quad \textbf{Eq. 8}$$

Solar hour Angle (ShA)
$$ShA = 15 * (hour + \frac{minute}{60} - \frac{15 - long}{15} - 12 + \frac{Eot}{60}) \quad \textbf{Eq. 9}$$

Solar altitude (SA)
$$SA = \frac{1}{K} * \arcsin((\sin(K * lat) * \sin(K * declin) + \cos(K * lat) * \cos(K * declin) * \cos(K * ShA)) \quad \textbf{Eq. 10}$$

A haul received the label "day" when for both, the beginning and the end, a positive solar altitude was calculated, the label "twilight" when only either result was positive, and the label "night" when the results for beginning and end time were negative.

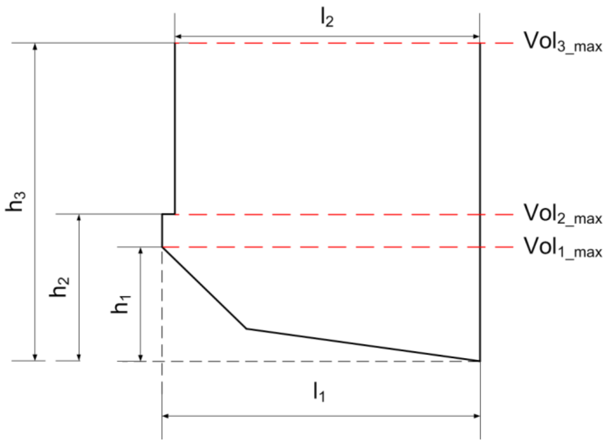
# 3 Results

The implementation of the HOVERCRAN system on a commercial vessel made it possible to generate a large number of hauls that can be evaluated. Data of 153 hauls were collected via self-sampling and a total of 39 hauls were conducted and processed with the group of scientists on board. The measurement of the stretched mesh size in the codend resulted in 19.6±0.1mm on starboard and 19.7±0.1mm on portside.

The results obtained in this study are presented in two parts, the self-sampling and the scientific-sampling as the vessel did not operate under fully commercial conditions during the latter. Note that all indications of the shrimp fraction always refer to the uncooked commercial shrimp fraction. Any time a "(Total) Shrimp Fraction" is mentioned the "total" refers to the fact that there are still small fish in this fraction. Undersized shrimp sorted out in the rotary sieve represent an independent fraction. There are also undersized shrimp sorted out by the shaking sieve which are not addressed directly, since they were not measured.

## 3.1 Calibration of hopper

Prior to measurement of the total catch volume, a conversion-factor between the measured height in the hopper to the volume was established. The hopper is irregularly formed which made it necessary to differentiate between three parts of the hopper for further calculations. A cross section of the hopper and the according equation are shown in Figure 10.The relation between height and volume for all three parts of the hopper is shown in Figure 11.




$$Vol_3(h) = Vol_{2max} + (h - h_2) * l_2 * w \qquad \textbf{Eq. 11}$$

$$Vol_2(h) = Vol_{1max} + (h - h_1) * l_1 * w \qquad \textbf{Eq. 12}$$

$$Vol_1(h) = \frac{b}{2a} + \sqrt{\left(\frac{b}{2a}\right)^2 - \frac{c-h}{a}} \qquad \textbf{Eq. 13}$$

**Figure 10: Cross section through the hopper (similar on both sides) viewed towards the back of the vessel and the according equations. The equations are valid within their respective height limits.**

where

*h*(eight) = measured height

$h_1$ = 33.5cm

$h_2$ = 44cm

*w*(idth of hopper) = 100cm

$l_1$ = 97cm

$l_1$ = 94cm

*a* = -2.993e-04

*b* = 1.751e-01

*c* = 9.654

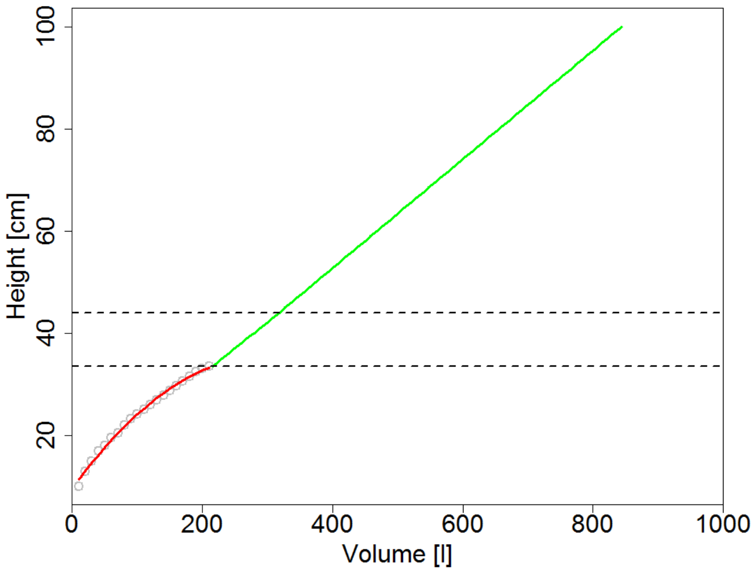



**Figure 11: Height-volume-relationship in the hopper in all three parts. The first part (red line) also contains the data from the volumetric measurement.**

## 3.2 Self-sampling

Most data sets were collected via self-sampling. Table 3 shows the number of data sets collected for each fraction of the catch. Data were analyzed based on absolute volumes, as well as based on the CPUE (Catch per Unit Effort). The CPUE used this study is the volume caught per hour. The application of the CPUE allows a standardization of the data. This is recommended as the towing duration varied between hauls. Figure 12 shows the fishing tracks and Table 4 gives a summary of the conditions during the self-sampling phase.

**Table 3: Overview of the number of data sets for each catch fraction according to the standard trawl (ST) and pulse trawl (PT). $n_{both}$ gives the number of hauls where information of both gears is available for the respective catch fraction. These hauls are used for further analysis.**

| | Volume | | | CPUE | | |
|---|---|---|---|---|---|---|
| | $n_{ST}$ | $n_{PT}$ | $n_{both}$ | $n_{ST}$ | $n_{PT}$ | $n_{both}$ |
| Total catch (TOT) | 144 | 146 | 144 | 117 | 117 | 116 |
| By-catch (BYC) | 141 | 146 | 141 | 114 | 118 | 114 |
| Total shrimp fraction (TOS) | 147 | 147 | 147 | 118 | 118 | 118 |
| A-shrimp (ASH) | 143 | 146 | 143 | 114 | 117 | 114 |
| B-shrimp (BSH) | 143 | 147 | 143 | 114 | 118 | 114 |

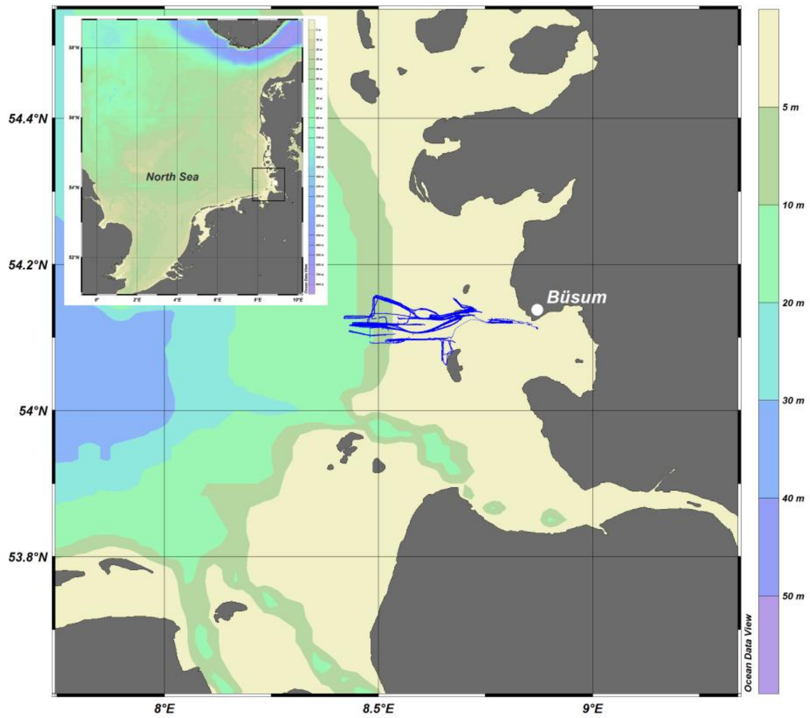



**Figure 12: Map of hauls conducted during the self-sampling phase of SD33 “Marlies”. The fishing tracks are marked dark blue.**

**Table 4: Summary of conditions during self-sampling phase**

| | |
|---|---|
| # Hauls overall | 153 |
| # Hauls June | 32 |
| # Hauls July | 89 |
| # Hauls August | 32 |
| # Hauls during day | 83 |
| # Hauls during twilight | 18 |
| # Hauls during night | 18 |
| # Average hauls per trip | 10 |
| Average trip duration | 21h |
| Average tow duration | 2.19h |
| Average towing speed | 2.7kn |
| Average salinity | 28 |
| Average temperature | 17.4°C |
| Average depth | 6m |

The number of hauls listed for the different times of day does not add up to the overall number of hauls. This is due to the fact that the bridge protocol filed by the fisherman, the HOVERCRAN log and the Star Oddi log did not always show the same time for beginning and end of a haul.

### 3.2.1 General analysis of fractions

The plot matrix provided in Figure 13 gives a general overview on the three most important fractions of the catch: total catch volume (TOT), shrimp fraction (TOS), by-catch (BYC). A detailed analysis of the individual fractions is given below. For reasons of clarity the two fractions of cooked shrimp excluded from this plot, but will presented later. The different colors mark the months in which the hauls took place. All fractions depicted are divided into standard trawl (ST) and pulse trawl (PT). The plot gives an overview of the correlations of fractions. A strong correlation between the gears within the fractions is shown, and there is also a correlation between the total catch and the shrimp fractions. The relation between the by-catch and the other two fractions is not as obvious. The correlations are not dependent on the month.

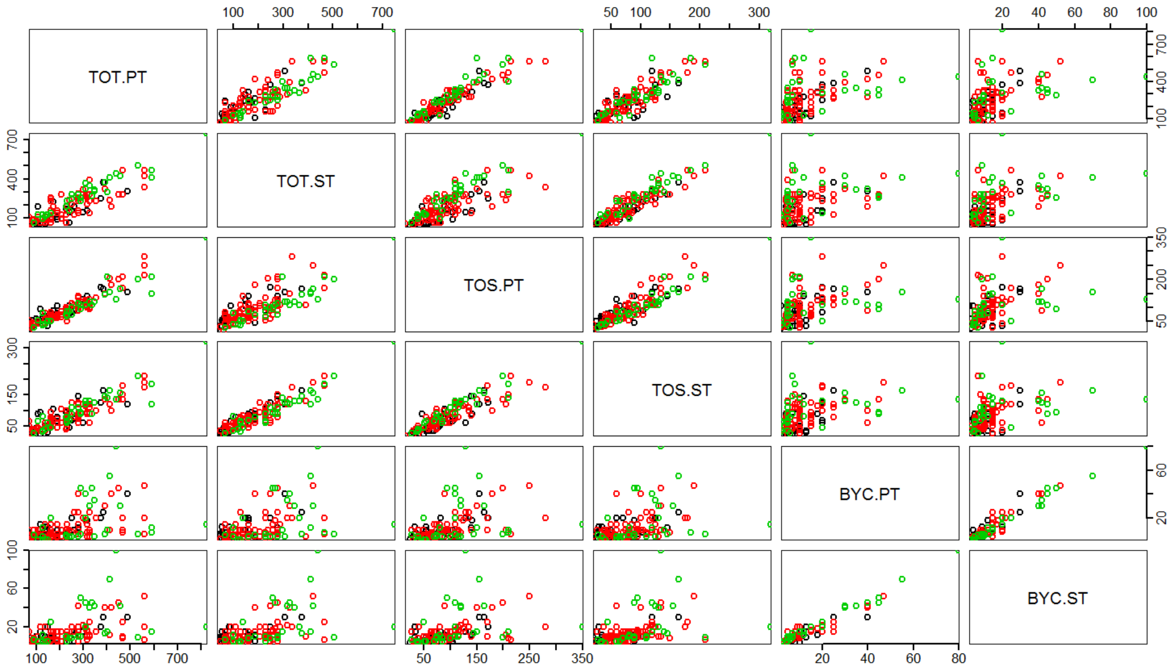



**Figure 13: Plot matrix of main fractions: total catch (TOT), shrimp fraction (TOS), by-catch (BYC) for both gears, separated by standard trawl (ST) and pulse trawl (PT). For all fractions, the volume is given in [l]. The colors resemble the months during which the haul was carried out: June (black), July (red), August (green)**

In order to quantify the share of each system in the overall volume in each fraction, for every haul the percentage of volume caught using the HOVERCRAN is calculated. The results are shown in Figure 14. The standard trawl caught the respective remaining percentage.

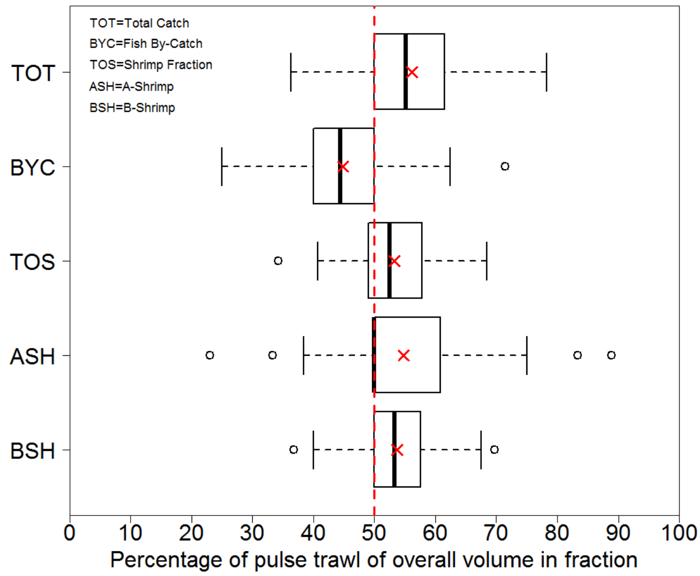


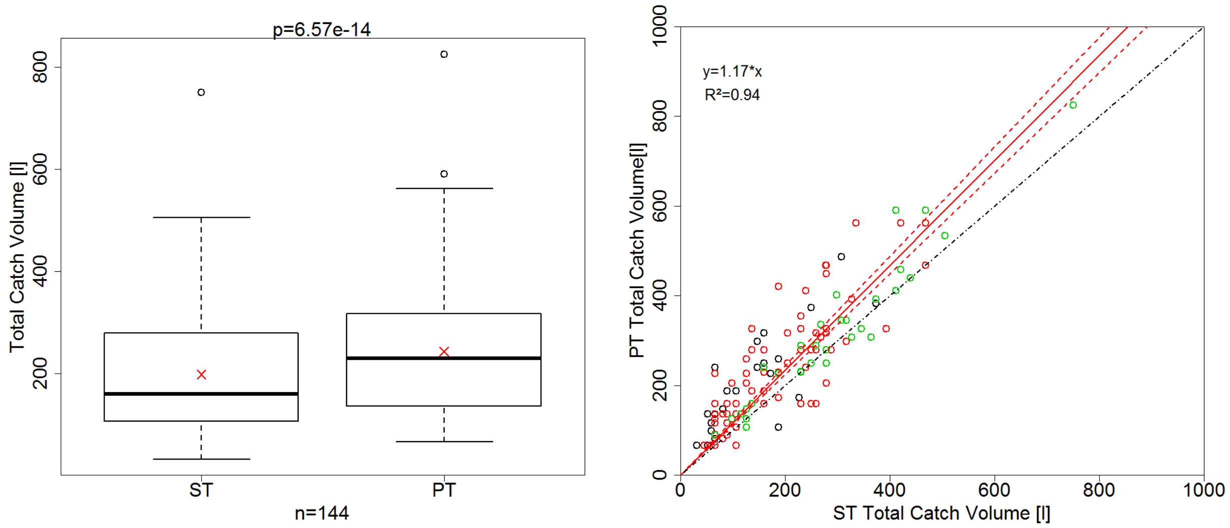

**Figure 14: Percentage of the volume caught using the HOVERCRAN in relation to the overall volume (volume ST + volume PT) in each fraction. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

The share of the HOVERCRAN in the total catch is more than 50% for most hauls with a mean value at 56%. The fraction "Fish by-Catch" includes all by-catch species large enough to be sorted out by the rotary sieve. The major part of this fraction is made up of a variety of fish species, swimming crabs (*Liocarcinus spp.*) and shore crabs (*Carcinus maenas*). A more detailed analysis of the by-catch is carried out in Chapter 3.3.3. The majority of hauls demonstrate that the share of by-catch obtained with the HOVERCRAN is less than 50% of the overall by-catch. The median and mean are both at approximately 44%. The shrimp fraction also includes fish that are too small to be sorted out with the rotary sieve or have a similar shape and width as *Crangon crangon*, e.g. sand goby (*Pomatoschistus minutus*), small hooknose (*Agonus cataphractus*) or small European smelt (*Osmerus eperlanus*) and are thus sorted together with the shrimp. In most cases, the pulse gear catches 50% or more of the overall shrimp fraction, i.e. the catches with the pulse trawl were equal to the standard trawl or slightly higher. Nonetheless, there are some hauls where the pulse gear had a poorer performance compared to the standard gear. The mean share of shrimp captured with the HOVERCRAN lies above the 50% mark, i.e. at 53%. More A-shrimp are caught using the pulse gear for most hauls. However, there are hauls where the major part of A-shrimp is obtained with the standard gear. This becomes obvious as the HOVERCRAN's share in the overall A-shrimp volume is lower than 50% for some hauls. A mean of 54% in comparison to the median at 50% can be observed. For many hauls, equal volumes were recorded for A-shrimp in both gears, resulting in a highly skewed distribution. More B-Shrimp were captured using the HOVERCRAN. The share of the HOVERCRAN varies between 50% and 57% for half of the hauls with a mean and median at 53%. A thorough analysis of the fractions and their relations will be carried out in the following chapters.

3.2.1.1 Total catch

The absolute volume, as well as the Catch per Unit Effort (CPUE) according to the gear are shown below.

**(A)**




**(B)**

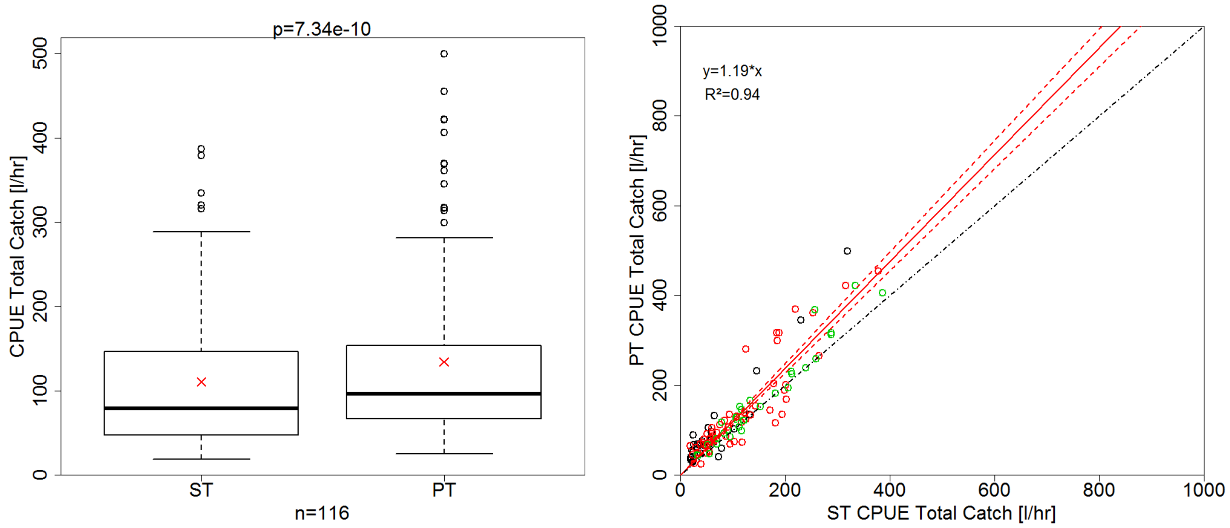
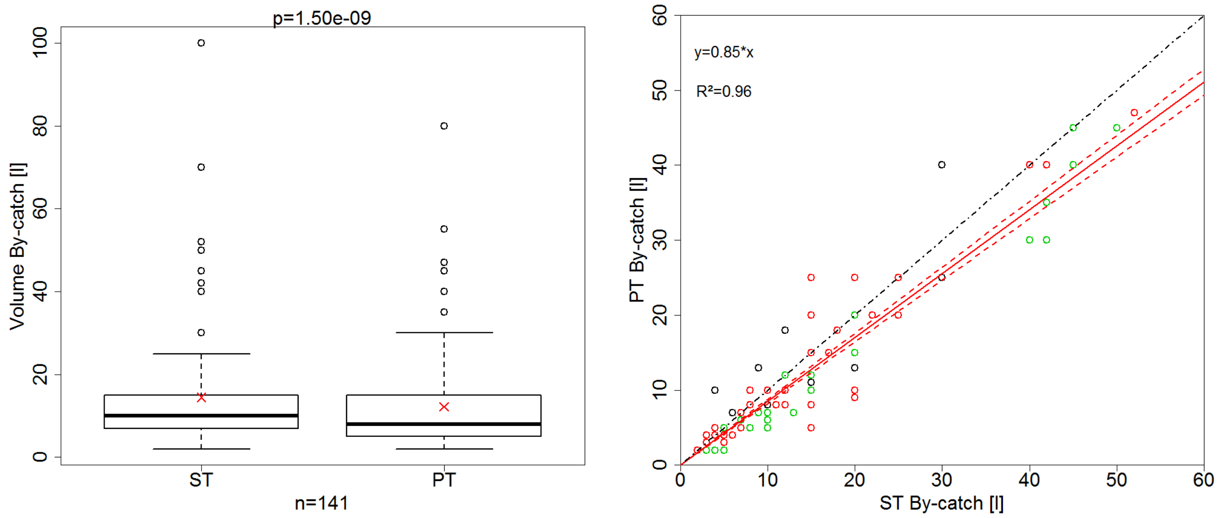



**Figure 15: Comparison of total catch for standard trawl (ST) and pulse trawl (PT) (A) Absolute total catch volume, (B) total catch as CPUE (l/h). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

With values far below the 0.05-mark, both the comparison of absolute volume as well as the CPUE of the total catch show significant differences between the standard and pulse trawl. The linear regression model confirms this result with the slope of the equation being greater than 1. The pulse gear showed 17% higher catches than the standard gear. A slope equal to 1, i.e. the identity line, would mean that the volume and CPUE respectively of the pulse and standard trawl are equal. A t-test confirmed that the slope is significantly different from 1. There is no visual difference to be detected between the months.

3.2.1.2 By-catch

**(A)**




**(B)**

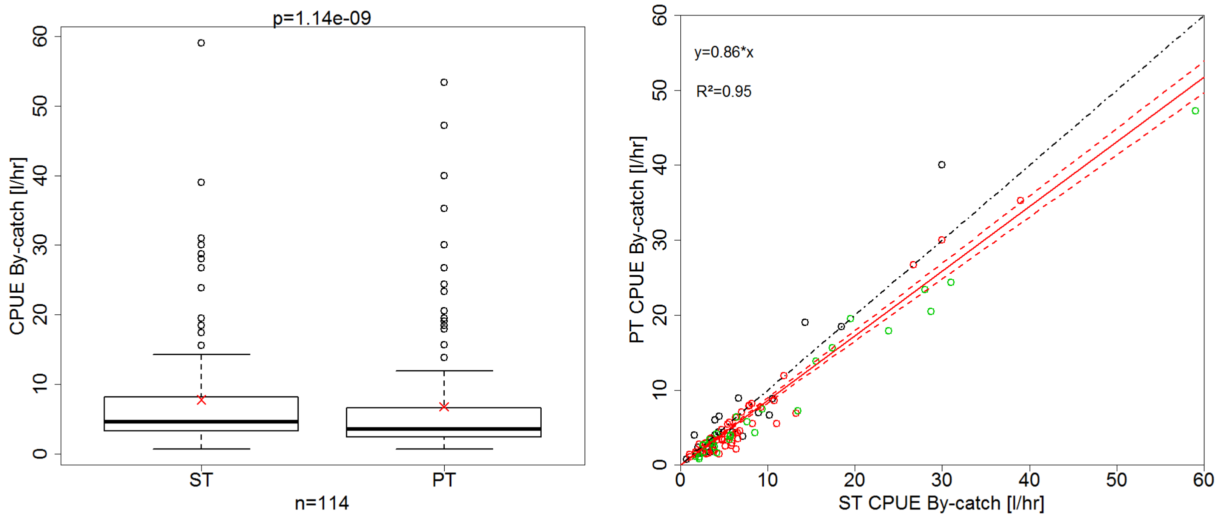



**Figure 16: Comparison of the by-catch for standard trawl (ST) and pulse trawl (PT) (A) Absolute by-catch volume, (B) by-catch as CPUE (l/h). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

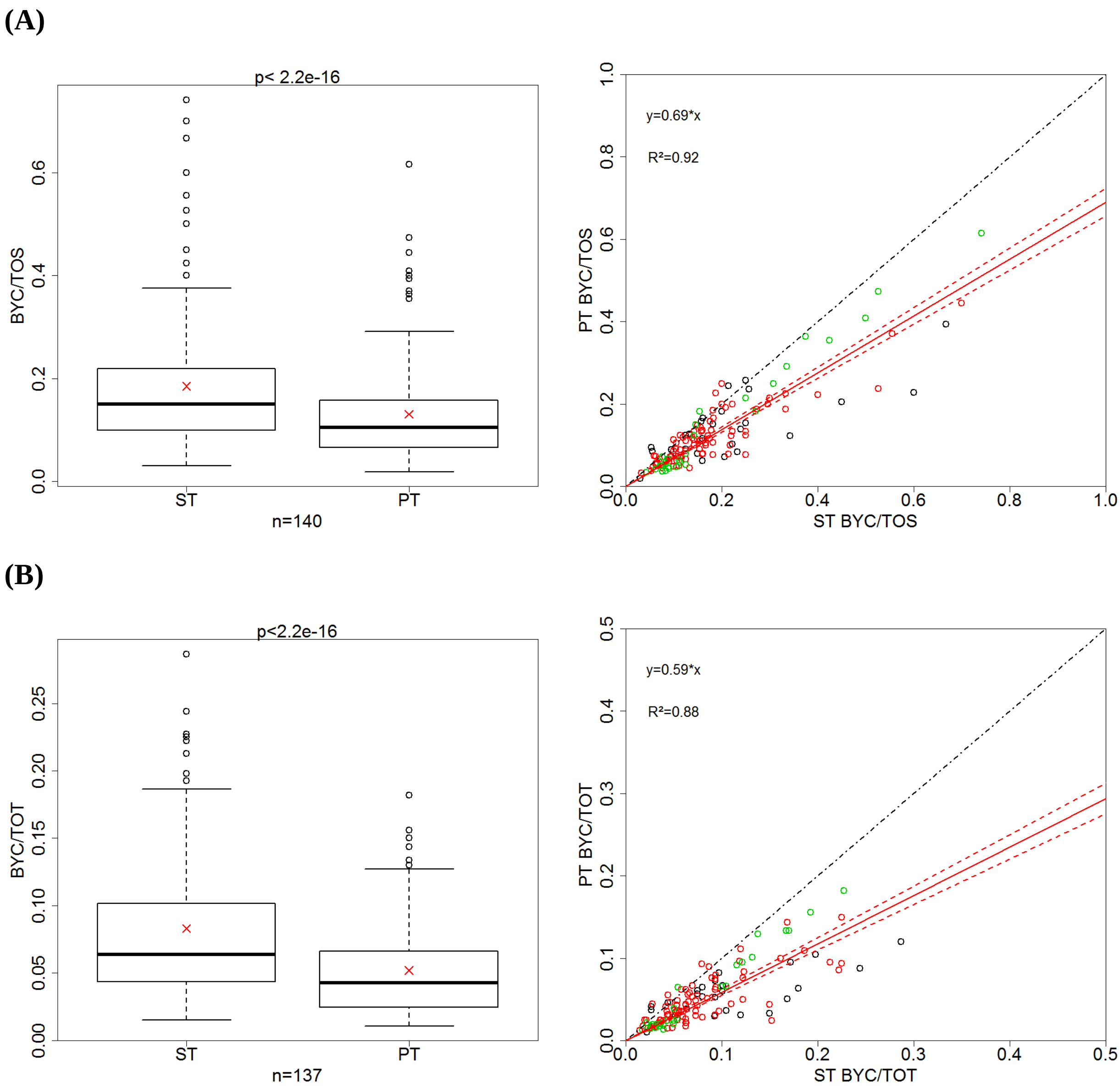



**Figure 17: Comparison of two ratios comprising the by-catch for standard trawl (ST) and pulse trawl (PT). (A) Ratio between by-catch and shrimp fraction, (B) Ratio between by-catch and total catch. The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

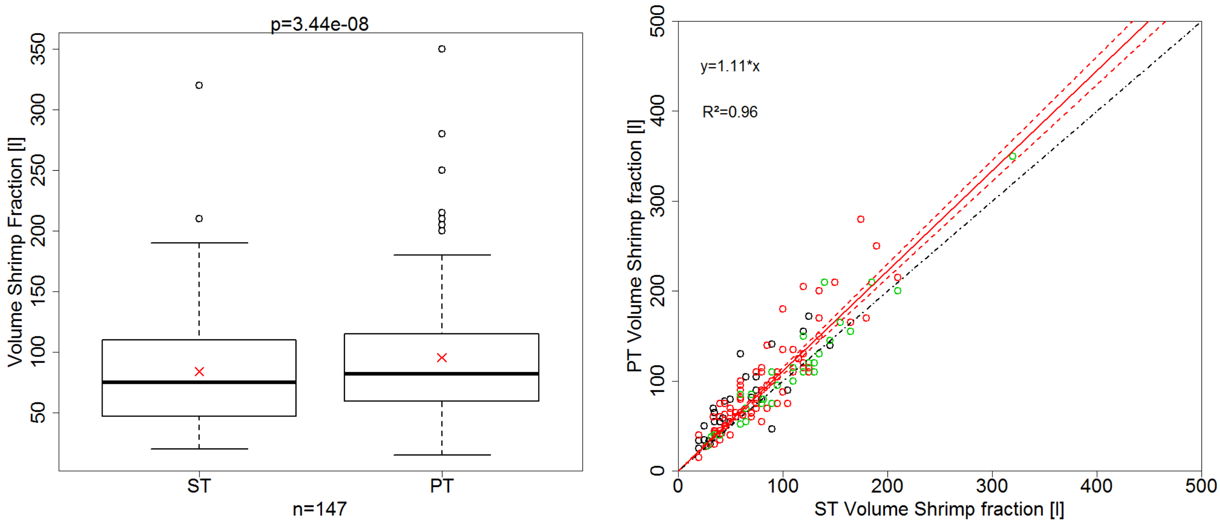
A tendency that more by-catch is produced using the standard gear is apparent (Figure 16). As the p-values indicate, there is a significant difference in by-catch volume and CPUE between the two gears. The linear regression resembles this outcome. Overall, there is 15% less by-catch produced with the pulse gear compared to the standard gear.

The relation between by-catch and shrimp is relevant. The greater the ratio the more by-catch is produced per amount of shrimp. A ratio of 0.5 or $\frac{1}{2}$ means, that 2 liters of shrimp require 1 liter of by-catch. Many data points lie below the 0.2 mark for both standard and pulse gear, however, there are also hauls where this relation is exceeded. The Wilcoxon Test shows a significant difference between starboard and portside. The linear regression model shows that more by-catch per liter of commercial shrimp is produced when using the standard gear as the slope is significantly smaller than 1.

When considering the ratio between by-catch and total catch, note that neither on starboard nor on portside more than 30% by-catch is recorded. The comparison between the two gears reveals a significant difference and that the share of by-catch in the total catch is higher in the standard gear catch.

## 3.2.1.3 Shrimp fraction

**(A)**




**(B)**

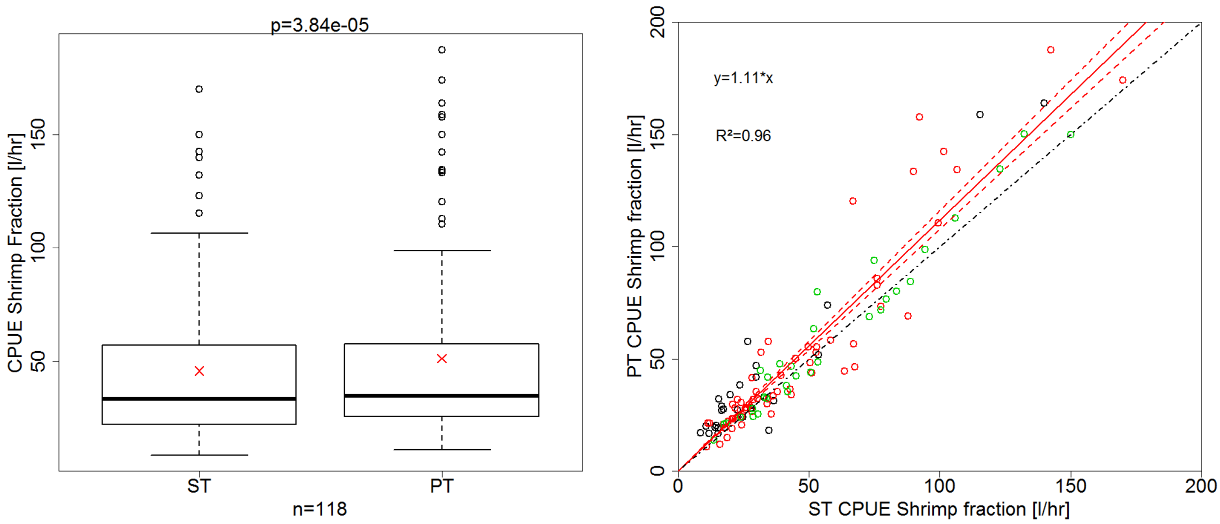
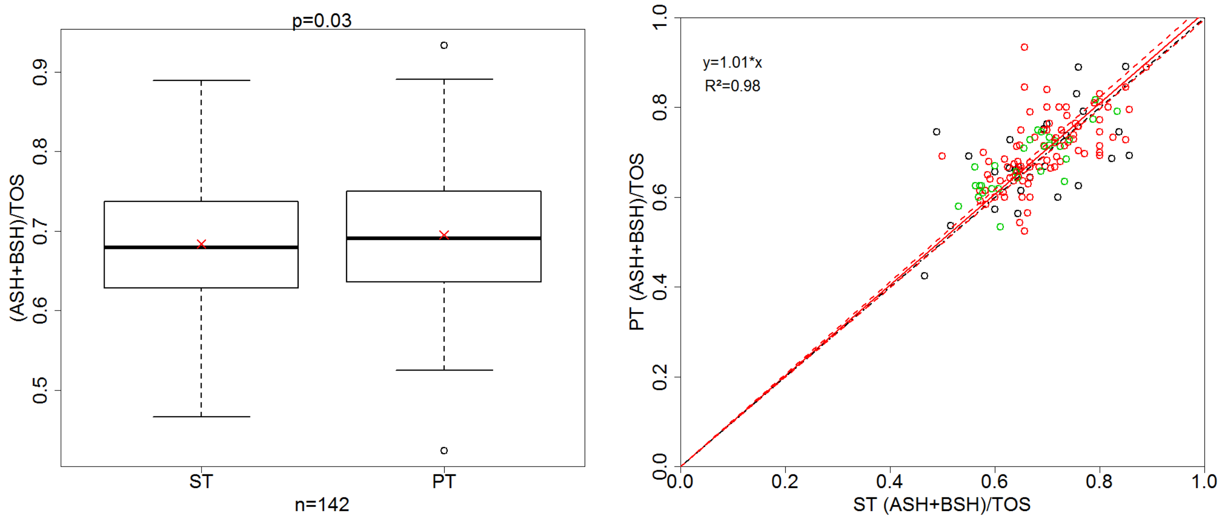



**Figure 18: Comparison of the total shrimp fraction for standard trawl (ST) and pulse trawl (PT) (A) Absolute shrimp fraction volume, (B) shrimp fraction as CPUE (l/h). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

**(A)**




**(B)**

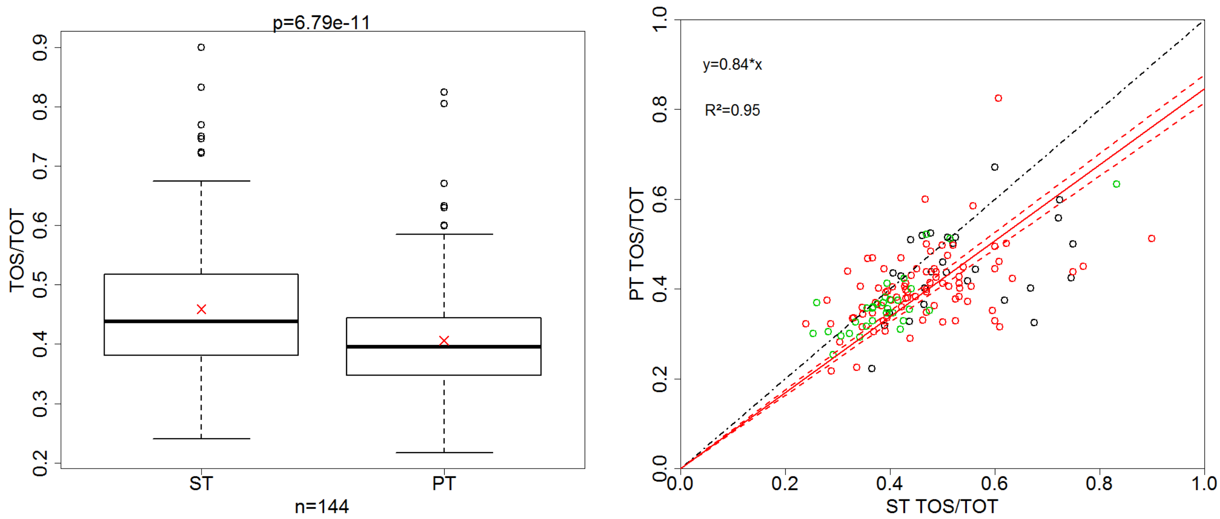



**Figure 19: Comparison of ratios comprising the shrimp fraction for standard trawl (ST) and pulse trawl (PT). (A) Ratio between cooked shrimp and shrimp fraction, (B) ratio between shrimp fraction and total catch. The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

A significant difference between the pulse and standard trawl regarding the shrimp fraction is present in the absolute volumes as well as the CPUE (Figure 18). Both, the Wilcoxon Test and the linear regression, show a trend towards a higher volume and CPUE when fishing with the HOVERCRAN. A catch increase of 10% is recorded when the HOVERCRAN is used. There is no obvious dependency of catch volume or catch rate on the month.

The relation between cooked shrimp and the shrimp fraction expresses the loss of volume after cooking. Figure 19(A) does not give a clear indication whether one gear performs better than the other. The evaluation of the linear regression model showed that the slope does not significantly differ from 1. However, the Wilcoxon Test states a difference between the two groups.

For both gears, the volume loss is approximately 30%. Theoretically, the relation between cooked shrimp and the shrimp fraction should be little lower than 1. A loss in volume when cooked, as well as the fact that there are small fish in the shrimp fraction, lower this ratio. Lastly, the fraction of C-shrimp is unaccounted for but nonetheless sorted out after cooking.

The second ratio of interest is the one between the shrimp fraction and the total catch. Both methods of evaluation show a significant difference between the standard and pulse trawl and both show the same result: a tendency of a higher ratio for standard trawl. This results means, that the share of shrimp in the total catch is higher when fishing with the standard gear. Generally, the commercial shrimp fraction makes up between 40% - 80% of the total catch.

## 3.2.1.4 Undersized shrimp

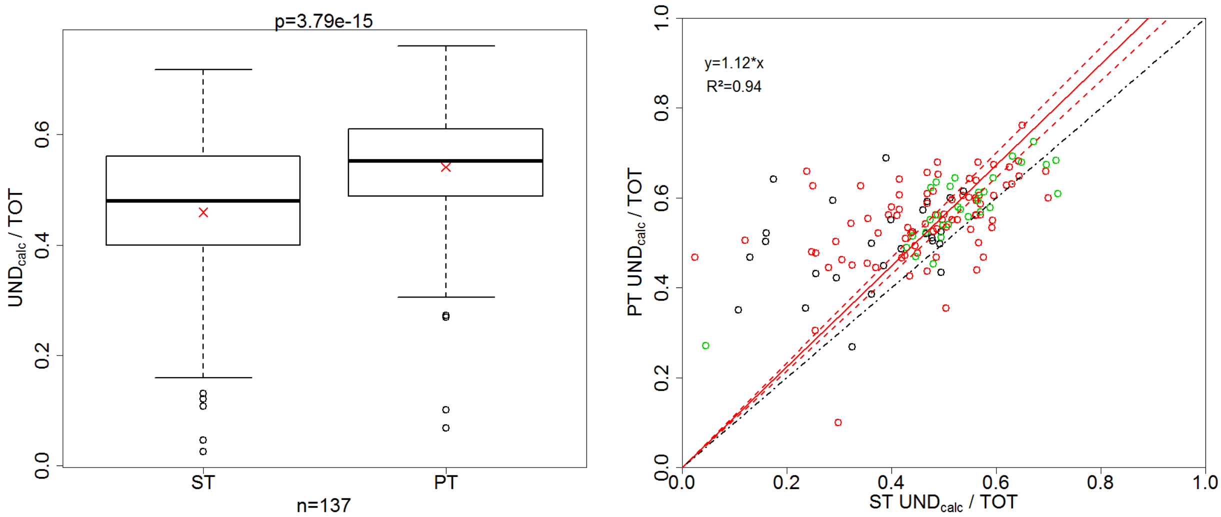
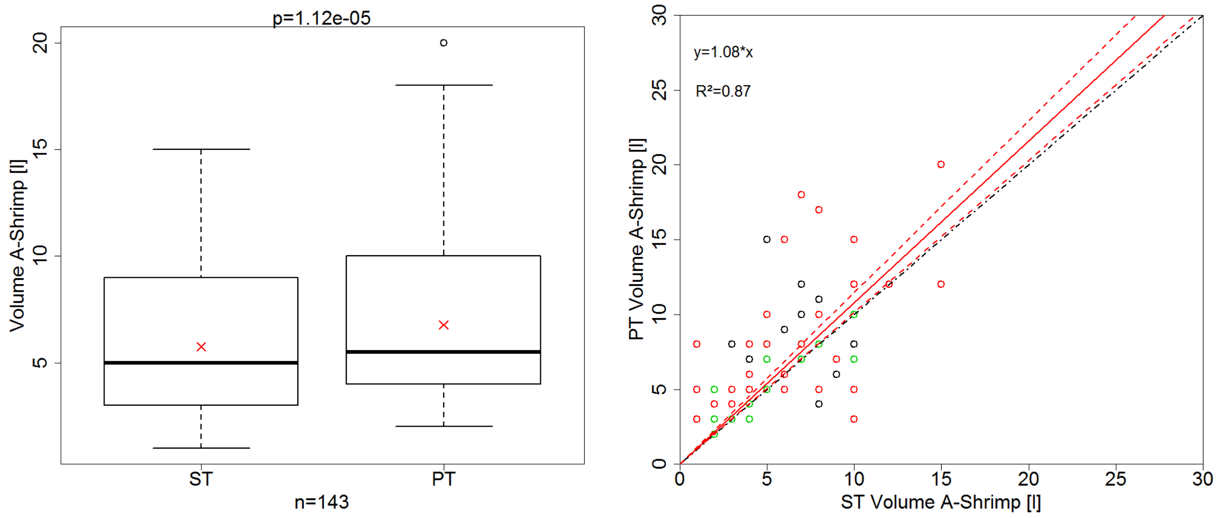



**Figure 20: Comparison of the ratio between calculated undersized shrimp and total catch for standard trawl (ST) and pulse trawl (PT). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

By subtracting the by-catch and the shrimp fraction from the total catch, the resulting value represents the undersized shrimp sorted out in the rotary sieve. As both, the Wilcoxon Test and the linear regression show, there is a significantly higher portion of undersized shrimp in the total catch of the pulse gear. These results are only calculated, a measurement of the actual volume of undersized shrimp is only carried out during the scientific-sampling.

## 3.2.1.5 A-shrimp

**(A)**




**(B)**

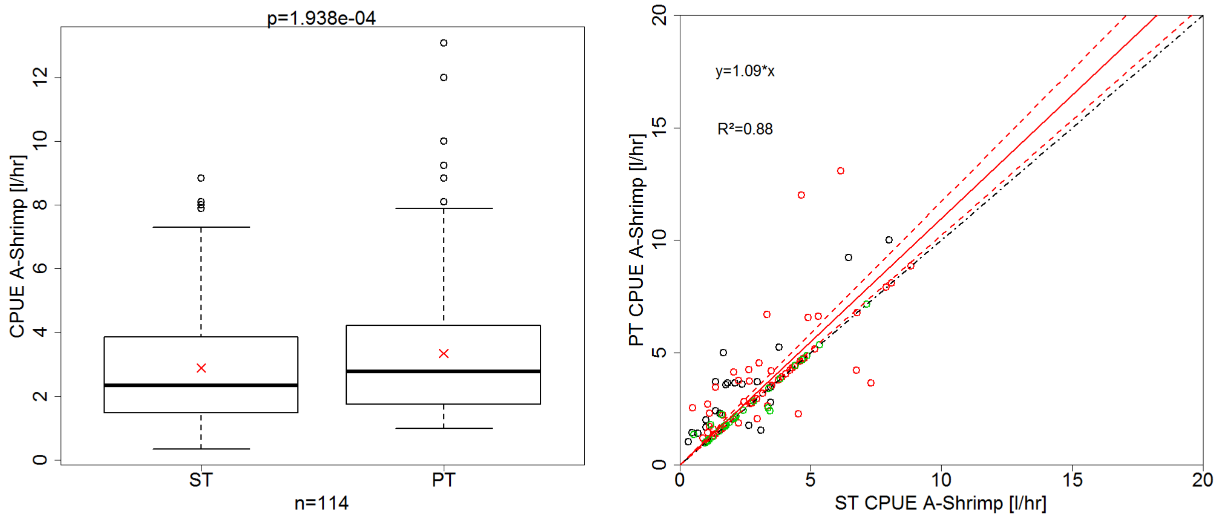
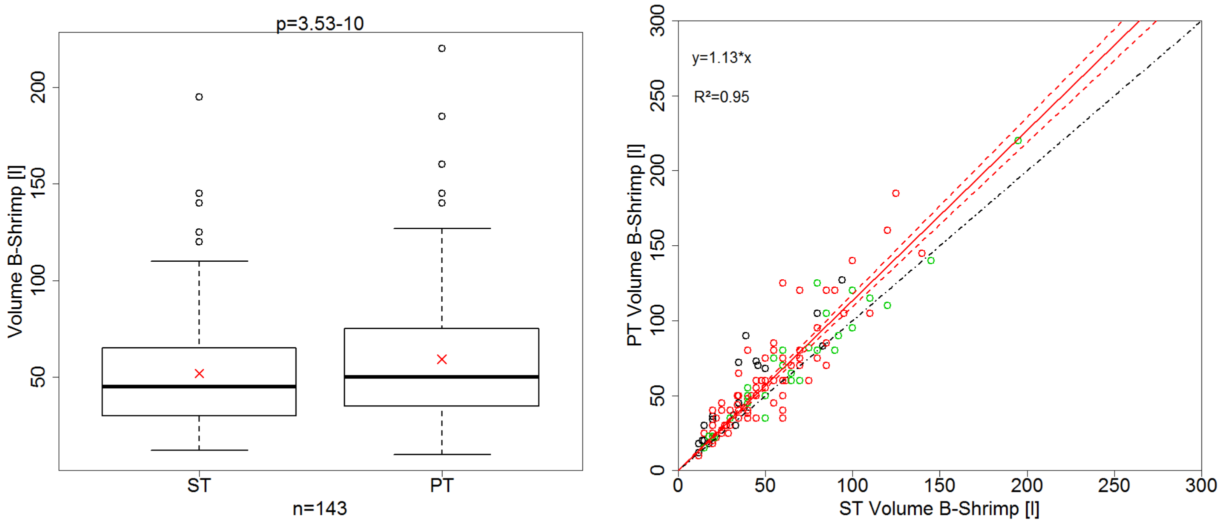



**Figure 21: Comparison of A-shrimp for standard trawl (ST) and pulse trawl (PT) (A) Absolute A-shrimp volume, (B) A-shrimp as CPUE (l/h). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

Both methods of evaluating the A-shrimp show a significant difference between the two groups in the absolute volume as well as CPUE. The scatterplot shows fewer combinations of values than the other fractions despite the equal number of data sets as for most fractions. The lack of combinations is caused by the coarse resolution of 1L used for the volume measurement of this fraction. The difference from a slope of 1 is not as distinct which is also shown by the larger confidence interval and the significance level is lower compared to the total catch.

3.2.1.6 B-shrimp

**(A)**




**(B)**

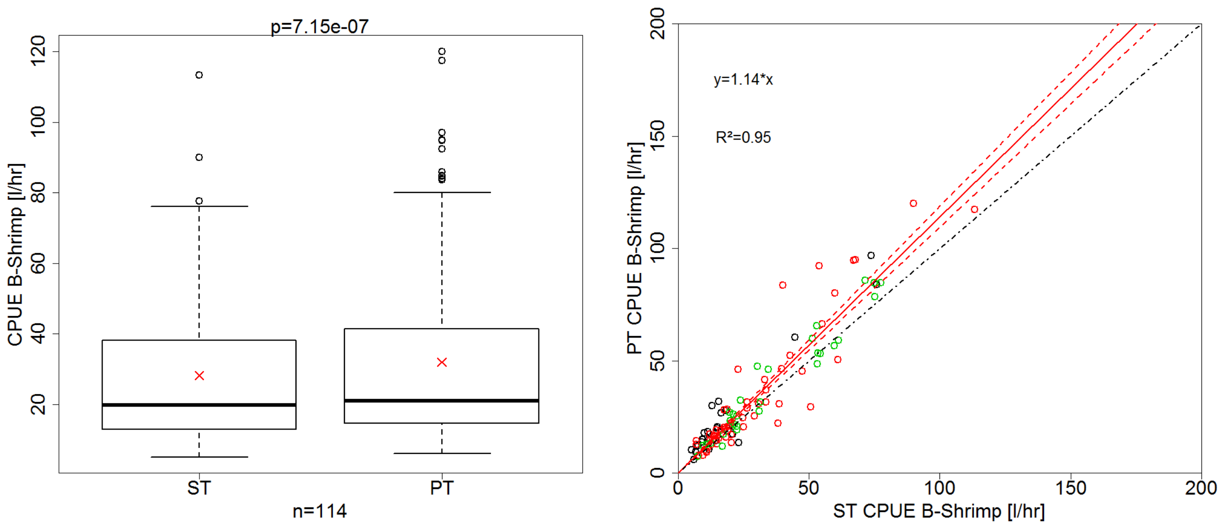



**Figure 22: Comparison of B-shrimp for standard trawl (ST) and pulse trawl (PT) (A) Absolute B-shrimp volume, (B) B-shrimp as CPUE (l/h). The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

The CPUE as well as the absolute volume of B-shrimp differ significantly between gears. A trend for a higher CPUE and volume when using the HOVERCRAN is evident, as the slope is significantly greater than 1. No monthly trend can be observed. The differences are more significant than in the A-shrimp fraction (Figure 21) as 14% more B-shrimp are produced using the HOVERCRAN compared to 8% of A-shrimp.

### 3.2.2 Comparison between day and night

A variety of parameters has a potential effect on the catchability of shrimps. During the self-sampling, a focus lay on the differences in catches according to the daytime, i.e. during the day, during twilight and during the night. The performance of the systems were compared among themselves, but also compared to one other regarding the different time aspects. Due to the fact that a much larger number of hauls was conducted during the day the absolute volumes are not compared, but rather the shares of the systems in the fractions. It is the same approach used for Figure 14. The Wilcoxon Test is carried out as the Wilcoxon Rank Sum Test for independent samples.

#### 3.2.2.1 Total catch

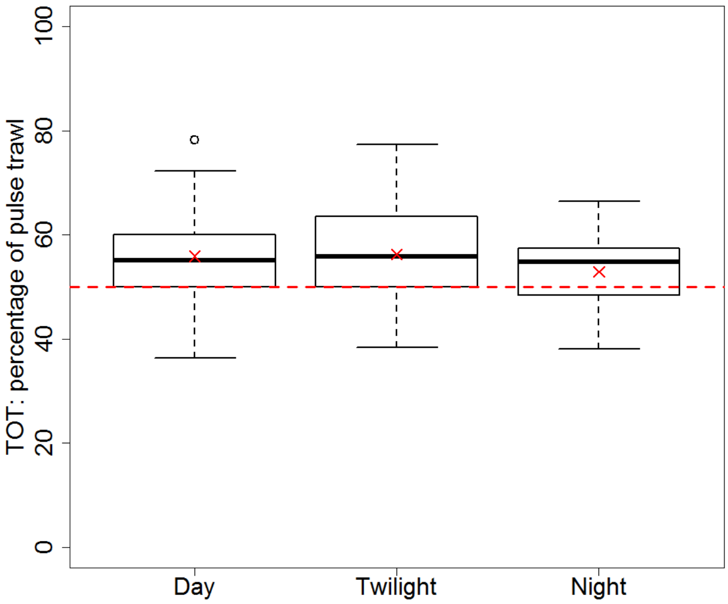



**Figure 23: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for the total catch volume (TOT) according to the time of day. The equilibrium between both gears (50%) is marked as red dashed line. The means are marked with a red cross.**

**Table 5: Results of the Wilcoxon Rank Sum Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for total catch (TOT). Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=82 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=82 | $ST_{twilight}$ n=18 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.8048 | | | | | |
| $PT_{night}$ | 0.2434 | 0.3138 | | | | |
| $ST_{day}$ | <2.20e-16* | 8.636e-06* | 0.0001214* | | | |
| $ST_{twilight}$ | 8.636e-06* | 0.0008364* | 0.01152* | 0.8048 | | |
| $ST_{night}$ | 0.0001214* | 0.01152* | 0.06771 | 0.2434 | 0.3138 | |

The comparison of the share on total catch between the two systems confirms the earlier results, that the HOVERCRAN has a greater efficiency than the standard gear. However, this is only valid during daytime and the hours around dusk and dawn. When the night catches are compared, there is no significant difference between the gears. Yet, the test shows no difference between night and day for either gear. The lack of difference may be caused by an insufficiently distinct difference within the gears and the higher efficiency only becomes overt when the two systems are compared. The balance of the shares during the night is also visible in Figure 23, as the mean is lying at 52% and a portion of hauls shows a share of the HOVERCRAN below the 50% mark.

### 3.2.2.2 By-catch

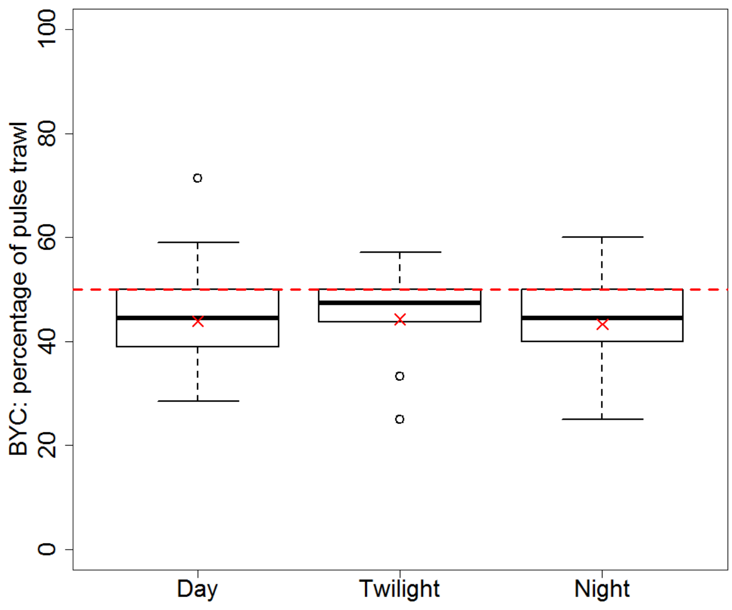



**Figure 24: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for the by-catch (BYC) according to the time of day. The equilibrium between both gears (50%) is marked as red dashed line. The means are marked with a red cross.**

**Table 6: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for by-catch. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=81 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=80 | $ST_{twilight}$ n=17 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.4122 | | | | | |
| $PT_{night}$ | 0.8702 | 0.497 | | | | |
| $ST_{day}$ | <2.2e-16* | 3.957e-06* | 1.612e-06* | | | |
| $ST_{twilight}$ | 3.957e-06* | 0.002441* | 0.0007878* | 0.4122 | | |
| $ST_{night}$ | 1.612e-06* | 0.0007878* | 0.0005075* | 0.8702 | 0.497 | |

In contrast to the total catch, there is a significant difference in by-catch between the gears at all hours. There is no difference within the gears at different times of day. The p-value is not as low during the dark hours as during daytime but nonetheless shows a highly significant difference. As Figure 24 shows, the share of the HOVERCRAN in the overall by-catch is lower than 50% with a few exceptions.

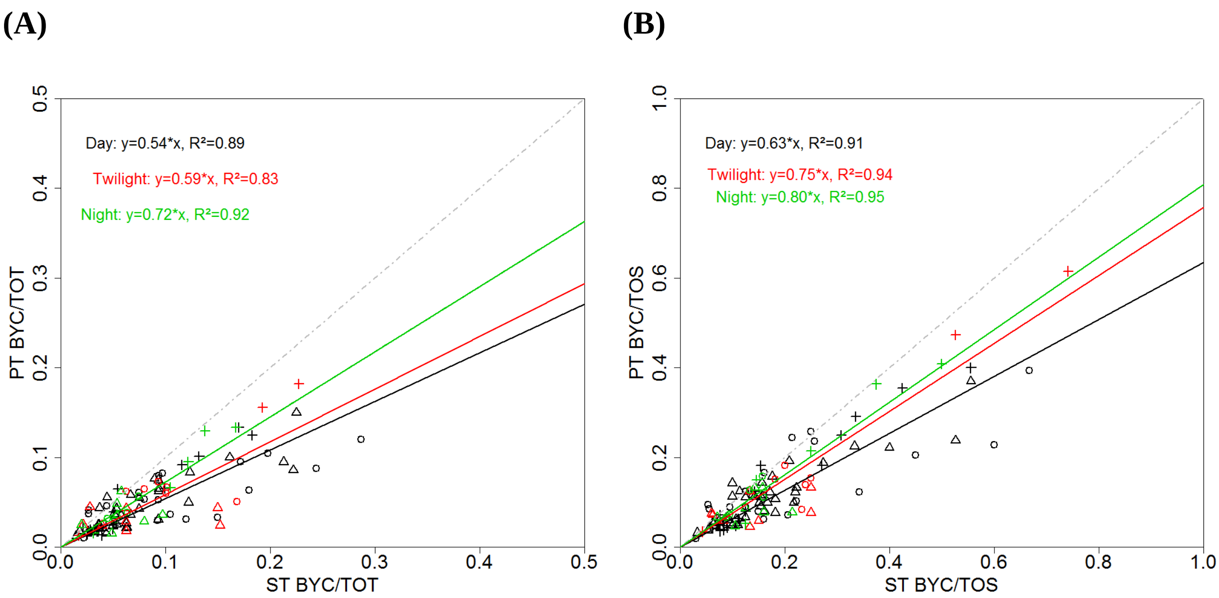



**Figure 25: Comparisons of ratios comprising the by-catch for standard trawl (ST) and pulse trawl (PT) according to the time of day. (A) Ratio between by-catch and total catch, (B) Ratio between by-catch and shrimp fraction. The months are shown in different symbols, the colors show different times of day: day (black), twilight (red), night (green). The solid are the linear regression for the times of day: day (black), twilight (red), night (green). The identity line is depicted as grey dashed-dotted line splitting the plot in half.**

**Table 7: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for the ratio between by-catch and total catch. Significant differences are marked with an asterisk**

| | $PT_{day}$ n=80 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=79 | $ST_{twilight}$ n=17 | $ST_{night}$ n=16 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.5883 | | | | | |
| $PT_{night}$ | 0.5509 | 0.9495 | | | | |
| $ST_{day}$ | 4.469e-13* | 0.04807* | 0.06411 | | | |
| $ST_{twilight}$ | 0.001213* | 0.001472* | 0.03453* | 0.2802 | | |
| $ST_{night}$ | 0.004095* | 0.05548 | 0.0001526* | 0.6155 | 0.3971 | |

**Table 8: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for the ratio between by-catch and shrimp fraction. Significant differences are marked with an asterisk**

| | $PT_{day}$ n=79 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=79 | $ST_{twilight}$ n=17 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.8508 | | | | | |
| $PT_{night}$ | 0.6763 | 0.8618 | | | | |
| $ST_{day}$ | 1.651e-11* | 0.06012 | 0.06678 | | | |
| $ST_{twilight}$ | 0.006834* | 0.001513* | 0.05947 | 0.3668 | | |
| $ST_{night}$ | 0.005114* | 0.04388* | 0.0005847* | 0.6449 | 0.5809 | |

The results of the tests comparing the ratio between by-catch and total catch show a significant difference between the gears during all three times of the day (Figure 25(A), Table 7). At night the slope of the model is closer to 1 than during the day. Nonetheless, a trend that more by-catch relative to the total catch is produced using the standard gear is given.

With less light, the slope of the linear model applied to the ratio between by-catch and shrimp increases (Figure 25(B)). For all three time frames it stays below 1 indicating a trend towards a higher ratio when using the standard gear. The Wilcoxon Test reveals the same result with a significant difference between the two groups (Table 8).

3.2.2.3 Shrimp fraction

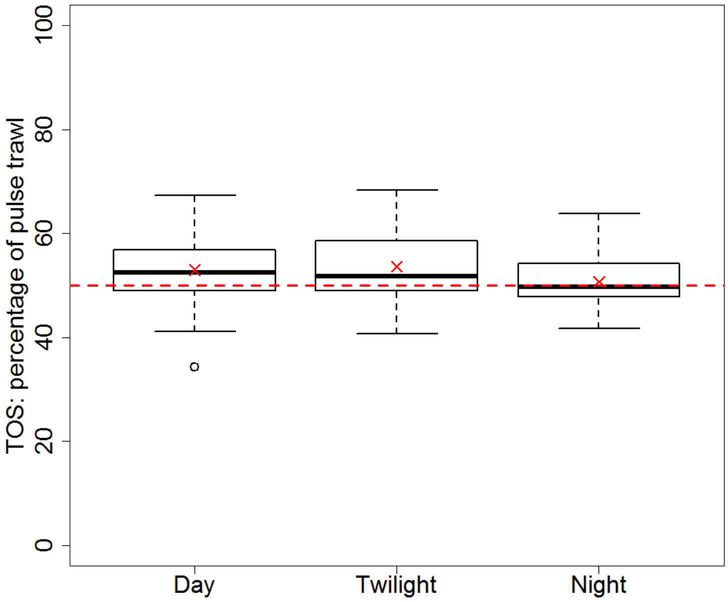



**Figure 26: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for the total shrimp fraction (TOS) according to the time of day. The equilibrium between both gears (50%) is marked as red dashed line. The means are marked with a red cross..**

**Table 9: Results of the Wilcoxon Rank Sum Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for shrimp fraction. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=82 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=82 | $ST_{twilight}$ n=18 | $ST_{night}$ n=18 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.9785 | | | | | |
| $PT_{night}$ | 0.08895 | 0.2108 | | | | |
| $ST_{day}$ | 4.704e-09* | 0.0009118* | 0.02369* | | | |
| $ST_{twilight}$ | 0.0009118* | 0.01081* | 0.1407 | 0.9785 | | |
| $ST_{night}$ | 0.02369* | 0.1407 | 0.8991 | 0.08895 | 0.2108 | |

The less light there is, the more the catches are equalizing, leading to the same share in the overall shrimp fraction during dark. This behavior can only be detected when comparing the two gears and is not apparent within one gear itself. This means, it cannot be detected, whether the standard gear catches more at night, or the pulse gear performs worse than during the daylight.

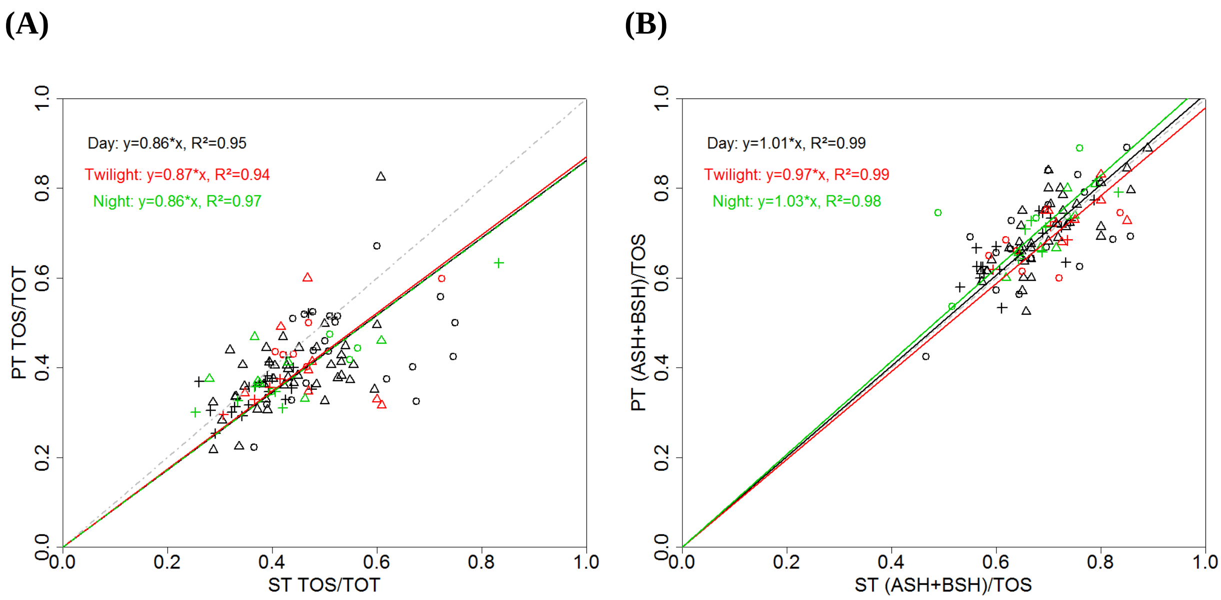



**Figure 27: Comparison of two ratios comprising the shrimp fraction for standard trawl (ST) and pulse trawl (PT) according to the time of day. (A) Ratio between shrimp fraction and total catch, (B) Ratio between cooked shrimp and shrimp fraction. The months are shown in different symbols, the colors show different times of day: day (black), twilight (red), night (green). The solid are the linear regression for the times of day: day (black), twilight (red), night (green). The identity line is depicted as grey dashed-dotted line splitting the plot in half.**

**Table 10: Results of the Wilcoxon Rank Sum Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for the ratio between shrimp fraction and total catch. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=82 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=82 | $ST_{twilight}$ n=18 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.709 | | | | | |
| $PT_{night}$ | 0.840 | 0.960 | | | | |
| $ST_{day}$ | 1.868e-06* | 0.1352 | 0.1006 | | | |
| $ST_{twilight}$ | 0.008124* | 0.05994** | 0.08164 | 0.677 | | |
| $ST_{night}$ | 0.1846 | 0.5034 | 0.02016* | 0.594 | 0.355 | |

**Table 11: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for the ratio between cooked shrimp and shrimp fraction. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=82 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=82 | $ST_{twilight}$ n=18 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.3095 | | | | | |
| $PT_{night}$ | 0.3052 | 1 | | | | |
| $ST_{day}$ | 0.0519 | 0.1342 | 0.1063 | | | |
| $ST_{twilight}$ | 0.2764 | 0.6777 | 0.8689 | 0.1492 | | |
| $ST_{night}$ | 0.9349 | 0.4962 | 0.1148 | 0.6968 | 0.3907 | |

Both the Wilcoxon Test and the linear regression model state that at any time of the day there is a significant difference between the standard and pulse gear when looking at the ratio between the shrimp fraction and the total catch. Note that the Wilcoxon Test for twilight is not as clear as the linear regression model.

The results for the ratio between landed shrimp (A-shrimp + B-shrimp) and the shrimp fraction prior to cooking show, that there is no significant difference between the two gears at any given time. Even though the slopes of the linear models cover a larger span than the ratio above, the t-test stated that the slope does not significantly differ from 1.

## 3.2.2.4 Undersized Shrimp

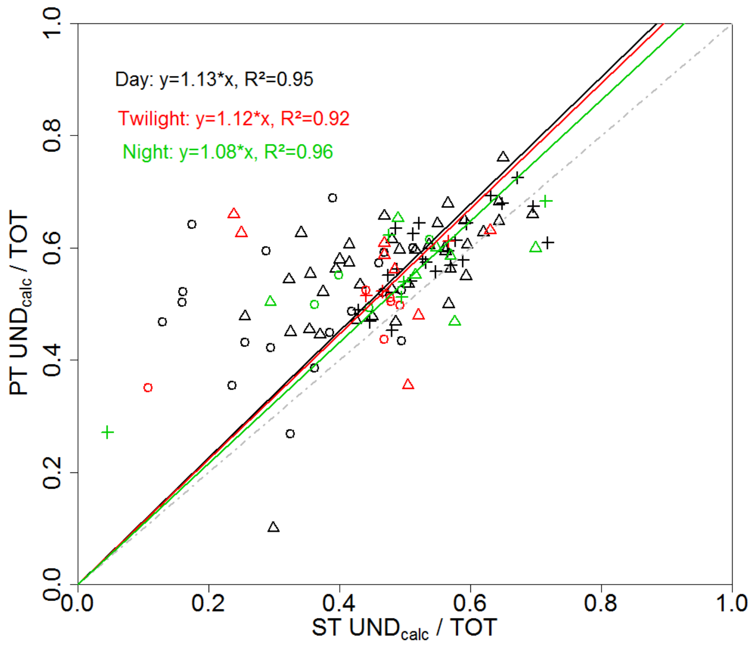



**Figure 28: Comparison of the ratio between calculated undersized shrimp and total catch for standard trawl (ST) and pulse trawl (PT) according to the time of day. The months are shown in different symbols, the colors show different times of day: day (black), twilight (red), night (green). The solid are the linear regression for the times of day: day (black), twilight (red), night (green). The identity line is depicted as grey dashed-dotted line splitting the plot in half.**

**Table 12: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for the ratio between calculated undersized shrimp and total catch. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=79 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=79 | $ST_{twilight}$ n=17 | $ST_{night}$ n=17 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.409 | | | | | |
| $PT_{night}$ | 0.7343 | 0.8391 | | | | |
| $ST_{day}$ | 5.79e-10* | 0.04553* | 0.02594* | | | |
| $ST_{twilight}$ | 0.0002998* | 0.01099* | 0.004506 | 0.393 | | |
| $ST_{night}$ | 0.0298* | 0.2373 | 0.0155* | 0.619 | 0.2138 | |

The undersized shrimp fraction is calculated by subtracting the by-catch and the shrimp fraction from the total catch. According to the Wilcoxon Test there is a difference between the gears at all times. The t-test carried out to evaluate the difference of the slope from 1, revealed that there is no difference at twilight and at night.

3.2.2.5 A-shrimp

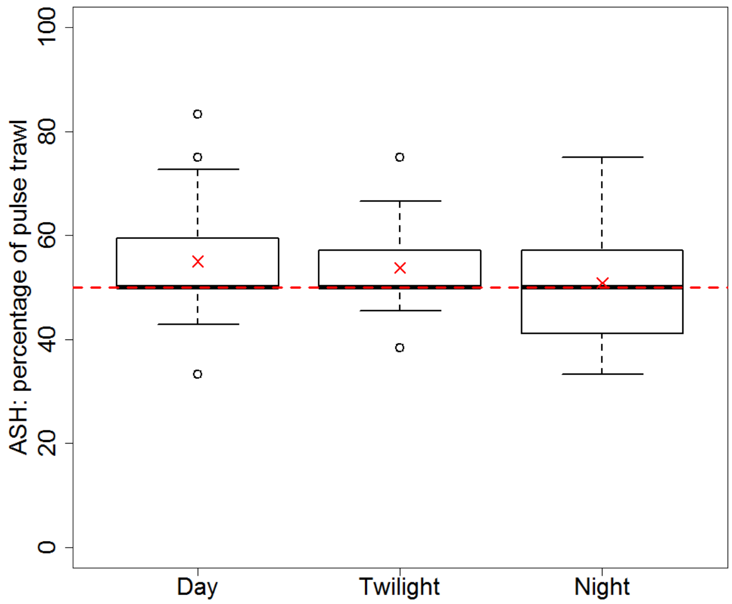



**Figure 29: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for the A-shrimp (ASH) according to the time of day. The equilibrium between both gears (50%) is marked as red dashed line. The means are marked with a red cross.**

**Table 13: Results of the Wilcoxon Rank Sum Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for A-shrimp. Significant differences are marked with an asterisk**

| | $PT_{day}$ n=81 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=79 | $ST_{twilight}$ n=17 | $ST_{night}$ n=18 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.7362 | | | | | |
| $PT_{night}$ | 0.09311 | 0.3141 | | | | |
| $ST_{day}$ | 1.203e-10* | 0.0004132* | 0.0655 | | | |
| $ST_{twilight}$ | 0.0004132* | 0.01801* | 0.2666 | 0.7362 | | |
| $ST_{night}$ | 0.0655 | 0.2666 | 0.8554 | 0.09311 | 0.3141 | |

As stated in the previous chapters, the performance of the gears differs significantly during the hours of light. Figure 29 shows a decreasing share of the HOVERCRAN in the A-shrimp with less light. At night, the catch of A-shrimp of the gears is comparable. The observed differences between night and day when comparing the two gears should result in a significant difference when the gears are compared within themselves at different times of day However, this is not the case, possibly due to the nature of the significance test.

3.2.2.6 B-shrimp

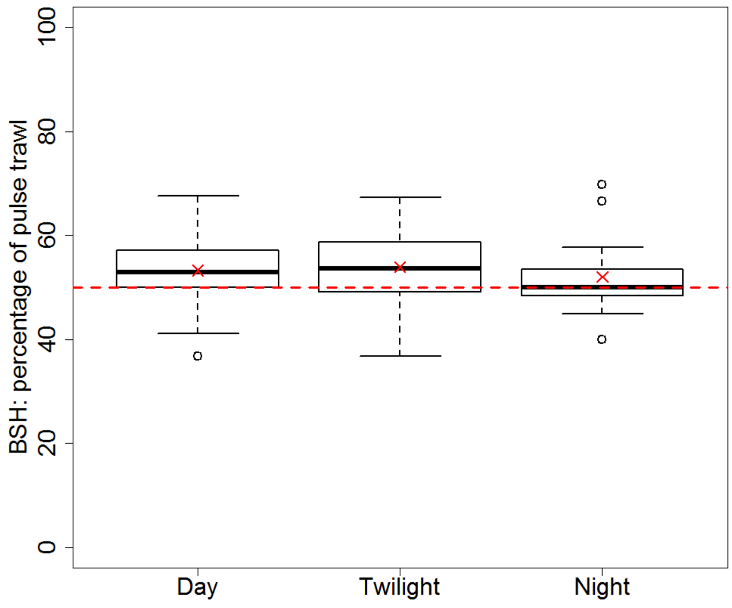



**Figure 30: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for the B-shrimp (BSH) according to the time of day. The equilibrium between both gears (50%) is marked as red dashed line. The means are marked with a red cross.**

**Table 14: Results of the Wilcoxon Rank Sum Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding time of day for B-shrimp. Significant differences are marked with an asterisk.**

| | $PT_{day}$ n=82 | $PT_{twilight}$ n=18 | $PT_{night}$ n=18 | $ST_{day}$ n=79 | $ST_{twilight}$ n=17 | $ST_{night}$ n=18 |
|---|---|---|---|---|---|---|
| $PT_{day}$ | | | | | | |
| $PT_{twilight}$ | 0.8626 | | | | | |
| $PT_{night}$ | 0.1694 | 0.3542 | | | | |
| $ST_{day}$ | 2.422e-10* | 0.0003624* | 0.00339* | | | |
| $ST_{twilight}$ | 0.0003624* | 0.003051* | 0.0509** | 0.8626 | | |
| $ST_{night}$ | 0.00339* | 0.0509** | 0.2524 | 0.1694 | 0.3542 | |

With less light, the share of the HOVERCRAN and the standard gear draw closer together. The improved performance of the standard gear or the worse performance of the pulse gear with less light is not as evident as in the evaluation of the A-shrimp (Figure 29). The difference between the gears decreases during twilight and vanishes at night. As in the A-shrimp, the difference in performance of the gears cannot be observed by comparing one gear within itself.

## 3.3 Scientific-sampling

During the scientific-sampling phase, more detailed data were collected and hauls were carried out under different aspects. Figure 31 shows the fishing tracks and Table 15 provides a summary of the conditions during the scientific-sampling. The remote tracks are located in the Elbe estuary where hauls at low salinity were carried out. Table 16 shows the number of data sets for each fraction.

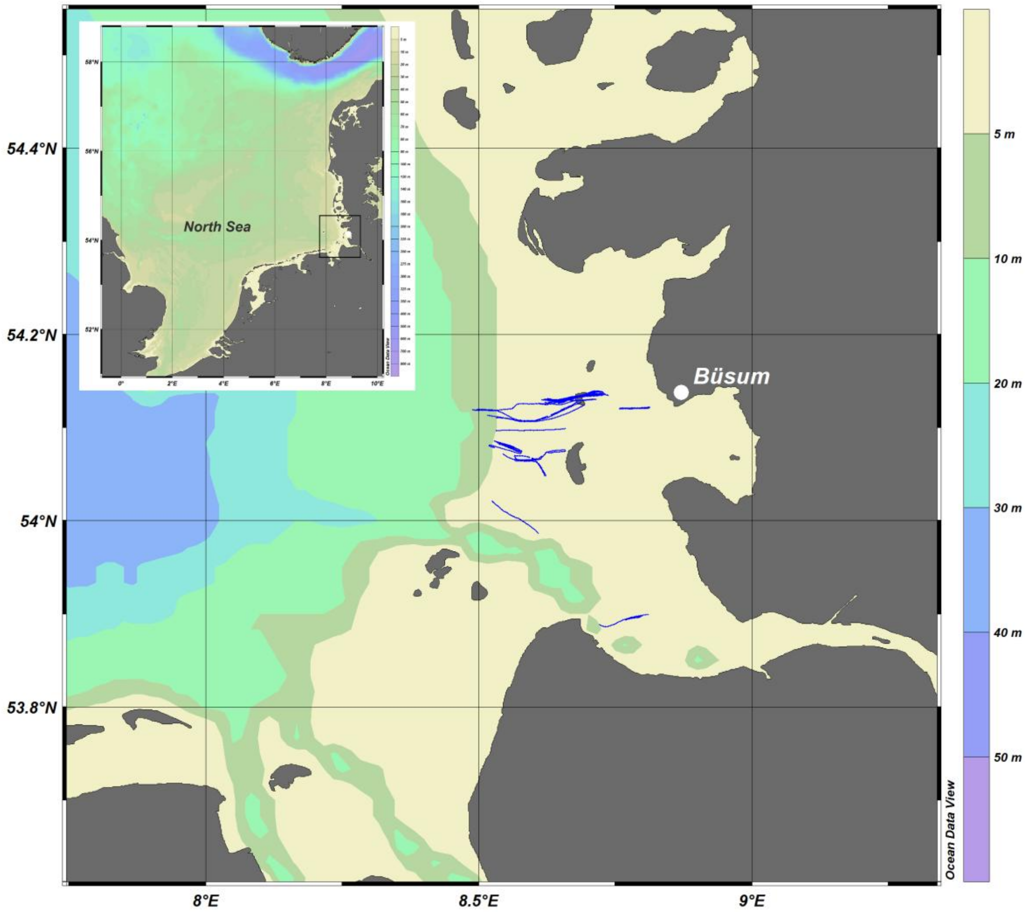



**Figure 31: Map of hauls conducted during the scientific-sampling phase of SD33 "Marlies". The fishing tracks are marked dark blue.**

**Table 15: Summary of the conditions during scientific-sampling phase on SD33**

| | |
|---|---|
| # Hauls overall | 39 |
| # Hauls during day | 34 |
| # Hauls during twilight | 2 |
| # Hauls during night | 3 |
| # Average hauls per 24h | 5 |
| Average trip duration | 12h |
| Average tow duration | 1.3h |
| # Hauls with salinity=16 | 3 |
| # Hauls with controlled towing speed ~ 3.5kn | 5 |
| # Hauls with controlled towing speed ~ 3kn | 7 |
| # Hauls with controlled towing speed ~ 2.5kn | 4 |
| # Hauls without pulse | 5 |

**Table 16: Overview of number of data sets for each fraction according to the standard trawl (ST) and pulse trawl (PT). Only hauls with pulse are included. $n_{both}$ gives the number of hauls where information of both gears is available for the respective catch fraction. These hauls are used for further analysis.**

| | Volume | | | CPUE | | | Weight | | |
|---|---|---|---|---|---|---|---|---|---|
| | $n_{ST}$ | $n_{PT}$ | $n_{both}$ | $n_{ST}$ | $n_{PT}$ | $n_{both}$ | $n_{ST}$ | $n_{PT}$ | $n_{both}$ |
| Total catch (TOT) | 35 | 35 | 35 | 34 | 34 | 34 | | | |
| By-catch (BYC) | 34 | 35 | 34 | 33 | 33 | 33 | 34 | 34 | 34 |
| Shrimp fraction (TOS) | 35 | 35 | 35 | 34 | 34 | 34 | 34 | 34 | 34 |
| Undersized shrimp (UND) | 28 | 28 | 28 | 27 | 27 | 27 | 34 | 34 | 34 |
| A-shrimp (ASH) | 33 | 34 | 33 | 32 | 33 | 32 | | | |
| B-shrimp (BSH) | 33 | 34 | 33 | 32 | 33 | 32 | | | |

All data sets with *n*=35 include the very first trial of the HOVERCRAN before the self-sampling period started.

In addition to the determination of the volume for all fractions including the undersized shrimp, the weight of by-catch, the shrimp fraction and the undersized shrimp was measured.

Prior to the evaluation of the fractions, a volume-weight-relation was established (Figure 32). This allows considering only one quantity in the following chapters while always leaving the opportunity for converting the volume into weight and vice-versa.

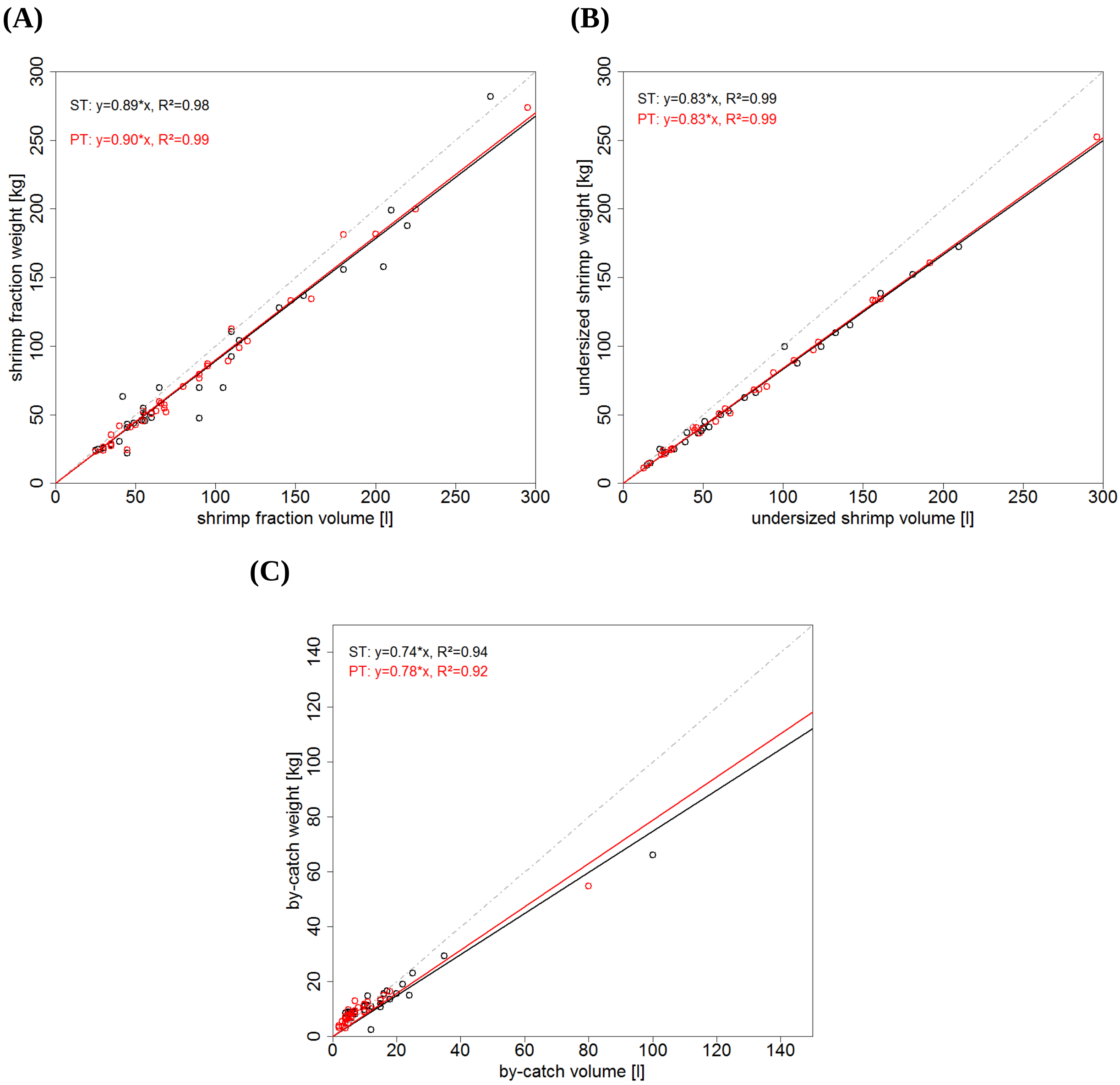



**Figure 32: Volume-weight-ratio for three fractions. The colors mark the two gears: standard trawl (ST, black) and pulse trawl (PT, red). (A) shrimp fraction, (B) undersized shrimp, (C) by-catch**

### 3.3.1 General analysis of fractions

The share of the HOVERCRAN in the overall catch of each fraction is shown in Figure 33 giving an overview of the data. Since a number of hauls were conducted without the pulse, only hauls with a functioning pulse gear were included.

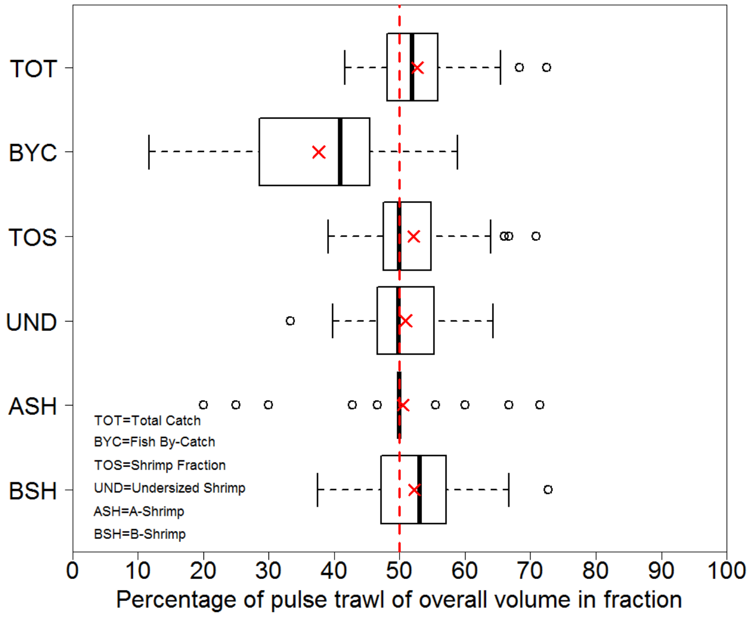


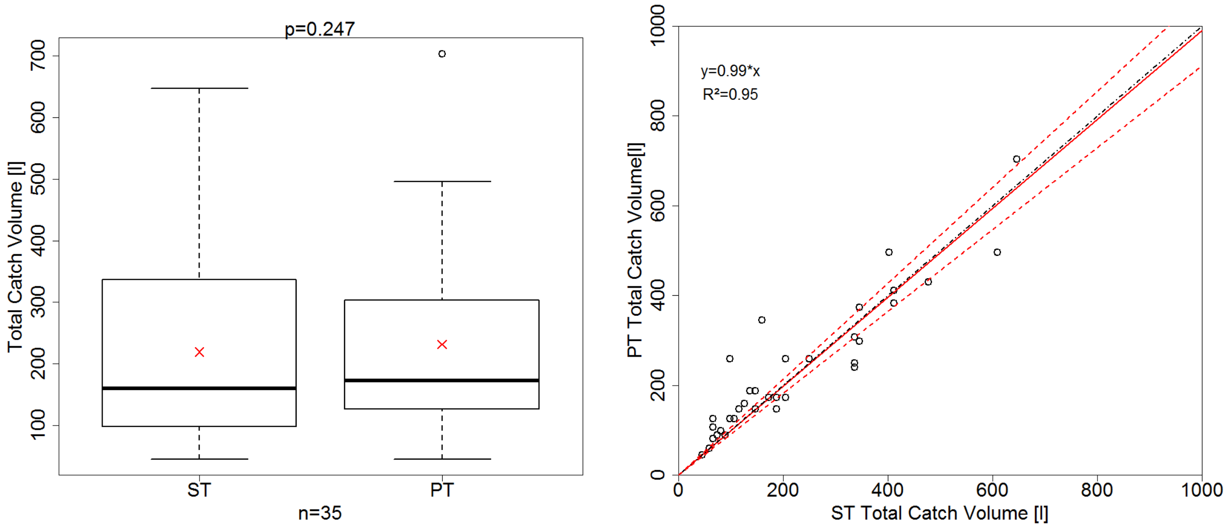

**Figure 33: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) in each fraction. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

Most values of the total catch lie above the 50% mark. There is a considerable amount of hauls where the standard gear had a greater share in the overall catch. Nearly all values concerning the share of by-catch by the pulse gear lie beneath 50% with a mean of 37%. The major part of the values of the shrimp fraction lies in the plus side of 50%. However, a notable amount of hauls show a smaller than half-share of the pulse gear in the total amount of shrimp caught. The fraction of undersized shrimp extends to both sides of the 50% mark, more specifically from 37% to 63% percent with a mean of 51%. There is one outlier at 33% which can be attributed to damage in the pulse gear net during that haul. The median is at 50%, the mean is 52%. When considering the fraction of larger cooked shrimp, it becomes evident that all but a few hauls resulted in an equal share for the pulse and the standard gear. The remaining hauls extend from 20% to 79%. Looking at the volume percentages of the B-Shrimp, the majority of the values state a higher share for the HOVERCRAN. Nonetheless there is a fraction that is lying underneath the 50% mark. The median lies at 53%, the mean at 52%.

The fractions were subject to tests on significant differences. Due to the non-normal distribution of the values, the non-parametric Wilcoxon Sign Rank Test for paired samples was applied as in Chapter 3.2. Since there are less data points, the Shapiro-Wilk Test for smaller samples was used for a testing of normal distribution. In this section, only the total catch, the by-catch, the shrimp fraction and the undersized shrimp and will be evaluated thoroughly, as they were the target fractions during this sampling period.

3.3.1.1 Total catch

**(A)**




**(B)**

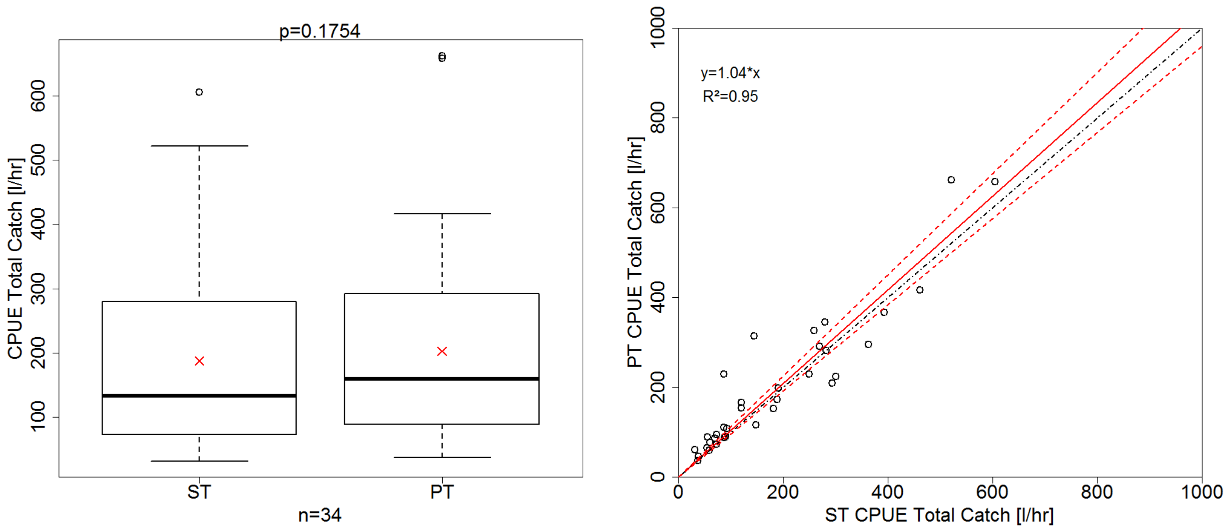
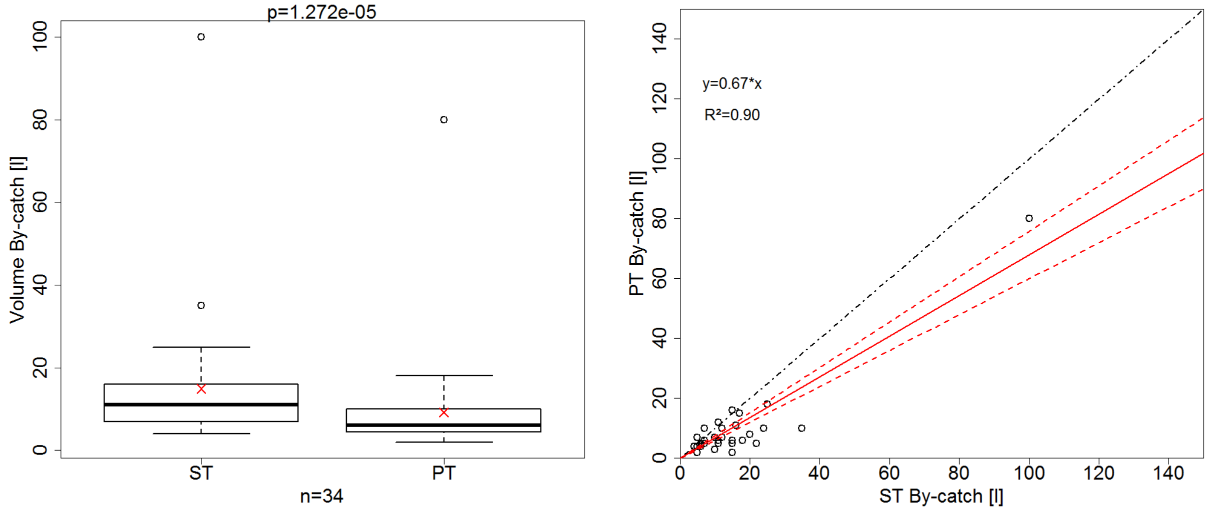



**Figure 34: Comparison of the total catch volume for standard trawl (ST) and pulse trawl (PT) (A) Absolute total catch volume, (B) total catch as CPUE (l/h) during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

In contrast to the results during the self-sampling, there is no significant difference between the pulse and the standard gear when considering the total catch. Neither the absolute volumes nor the CPUE show any difference.

### 3.3.1.2 By-catch

**(A)**




**(B)**

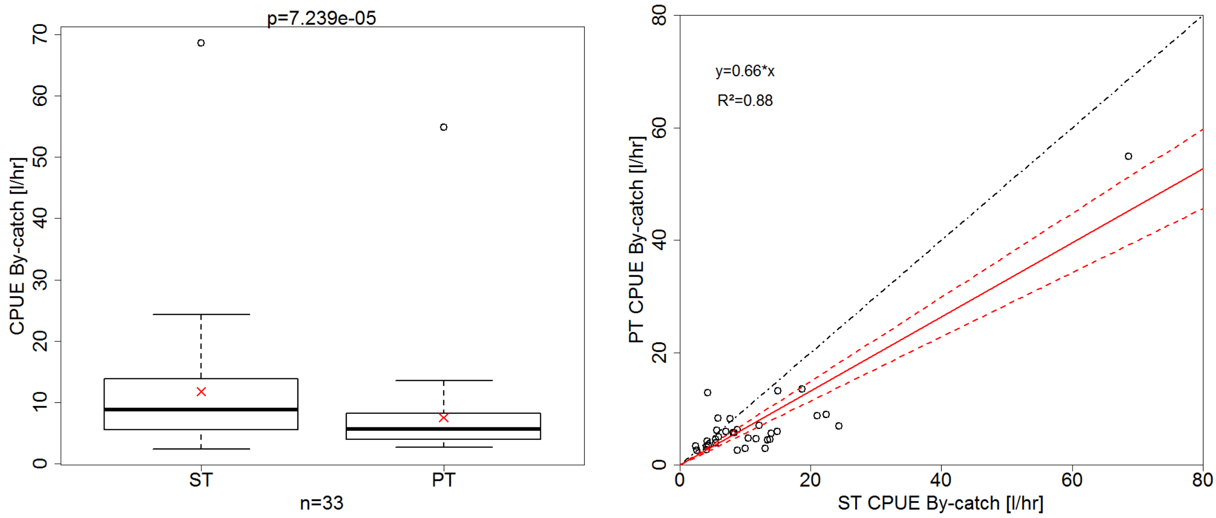



**Figure 35: Comparison of the by-catch for standard trawl (ST) and pulse trawl (PT) (A) Absolute by-catch volume, (B) by-catch as CPUE (l/h) during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

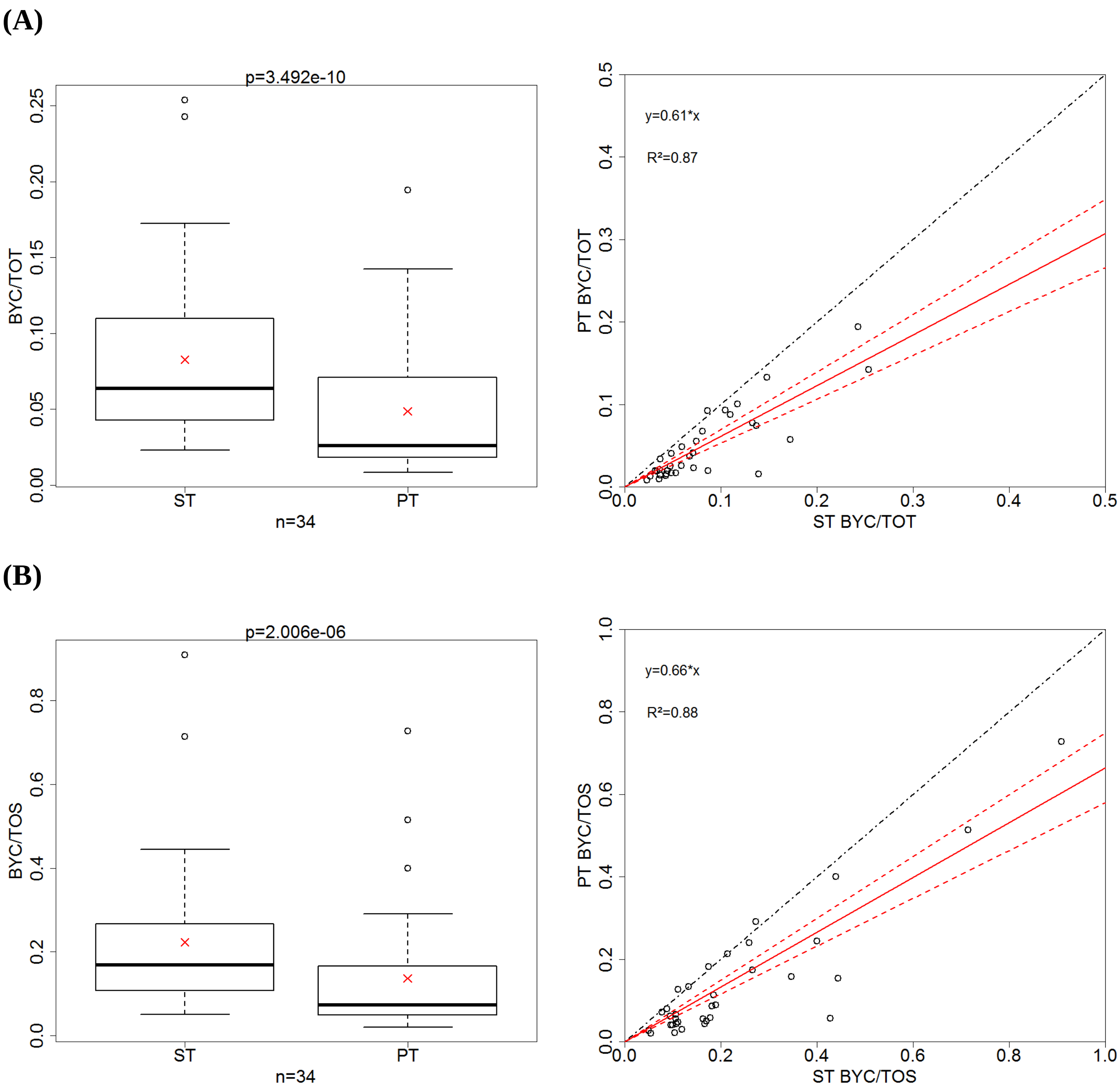
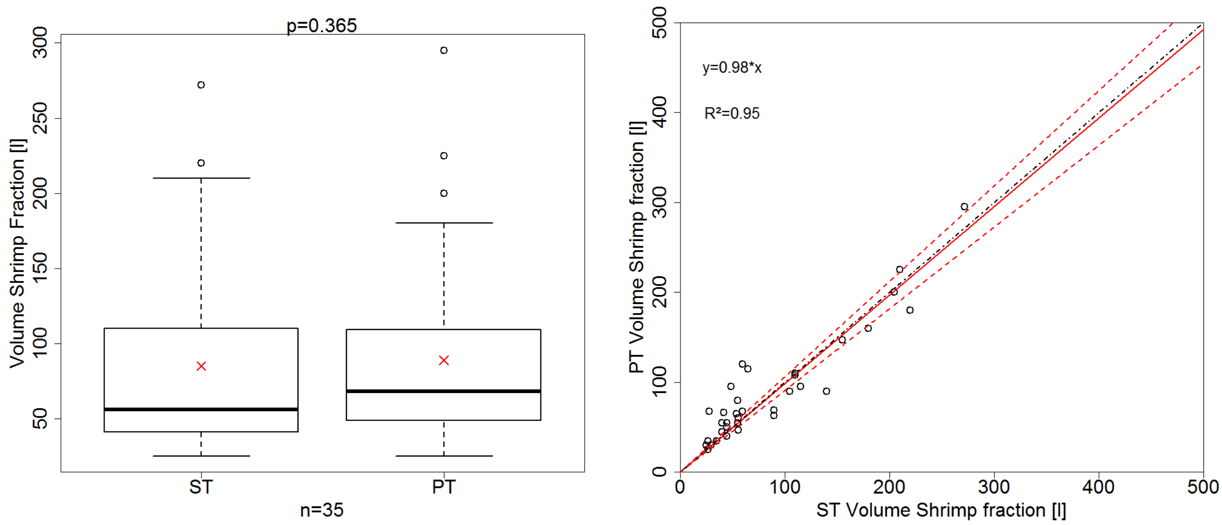



**Figure 36: Comparison of two ratios comprising the by-catch for standard trawl (ST) and pulse trawl (PT). (A) Ratio between by-catch and shrimp fraction, (B) Ratio between by-catch and total catch, during the self-sampling. The colors in the scatterplots mark the months during which the hauls were conducted: June (black), July (red), August (green). The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked as red crosses. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

Unlike all other fractions, the absolute volumes of the by-catch, as well as the CPUE differ significantly between the gears. More by-catch is produced using the standard gear. The ratio between by-catch and total catch does not exceed 0.3 for either one. In other words, no gear produced more than 30% by-catch in total. The significance tests show, however, that there is a difference between the standard and the pulse gear and that there is a trend of producing more by-catch in relation to the total catch when the standard gear is used. Additionally, the ratio between by-catch and the shrimp fraction is higher when using the standard gear and the gears differ significantly. This is not surprising since the same amount of shrimp is caught (Figure 37) and less by-catch is produced with the HOVERCRAN (Figure 35). Note, that there are a few data points with very high by-catch to shrimp fraction ratios, where as much as 9L of by-catch are produced for 10L of shrimp.

<u>3.3.1.3 Shrimp fraction</u>

**(A)**




**(B)**

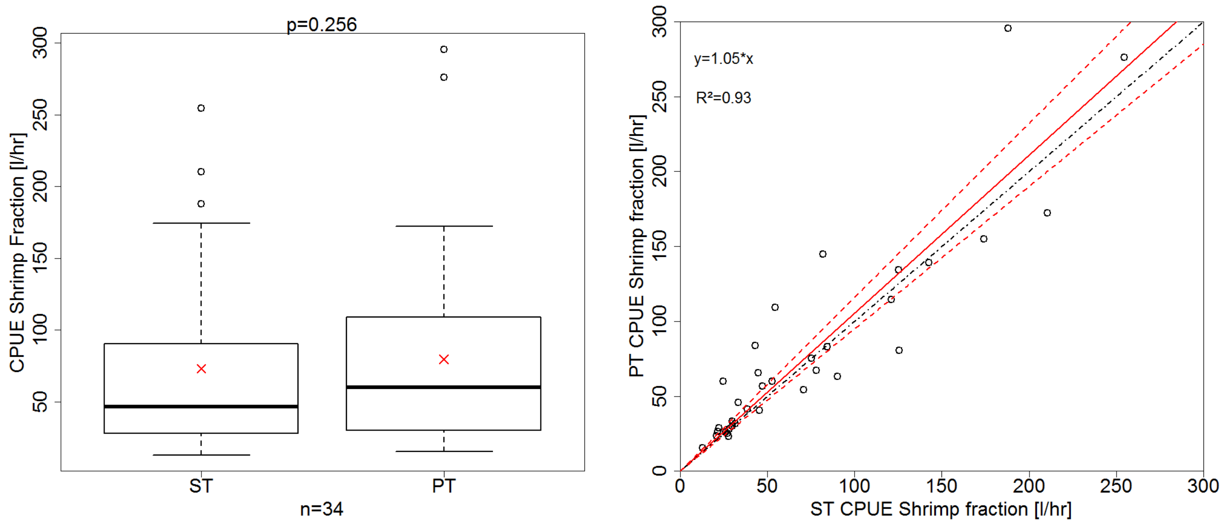



**Figure 37 Comparison of the shrimp fraction for standard trawl (ST) and pulse trawl (PT) (A) Absolute shrimp fraction volume, (B) shrimp fraction as CPUE (l/h) during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

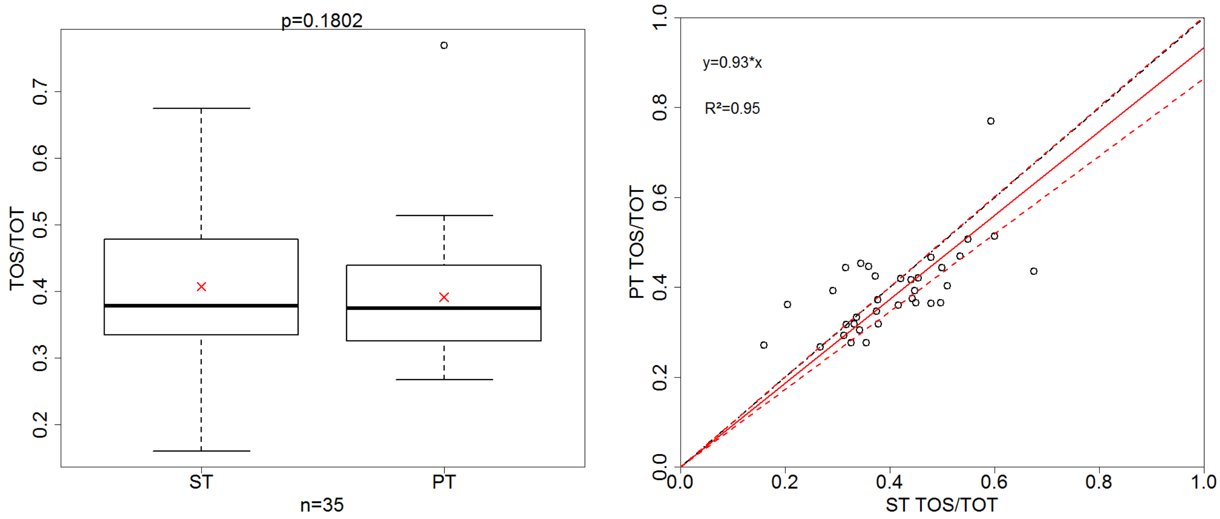



**Figure 38: Comparison of the ratio between shrimp fraction and total catch volume for standard trawl (ST) and pulse trawl (PT) during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

Neither the absolute volume nor the CPUE of the shrimp fraction differ between the standard and the pulse gear. Both, the linear model and the Wilcoxon Test show significance levels above the threshold of 0.05.

The ratio of the shrimp fraction to the total catch is significantly different, when the linear regression model is applied as an evaluation, whereas the Wilcoxon Test shows no significant difference. While of the Wilcoxon Test is more robust, it is also harder to detect very small differences using this test. There is a possibility that the signal is too weak to give an optimum basis for this non-parametric test.

As the total catches and the shrimp fraction are equal and there is less by-catch on the HOVERCRAN side, another fraction must necessarily fill in the remaining volume in the total catch of the pulse gear (Figure 39).

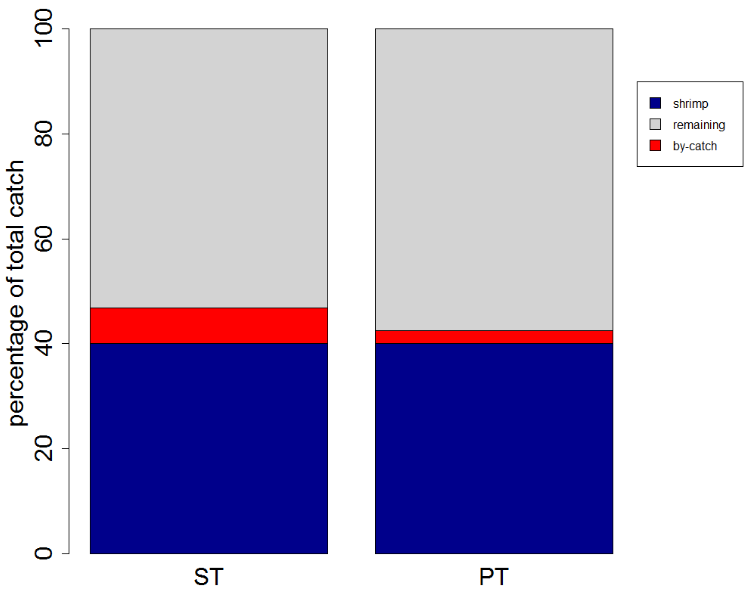
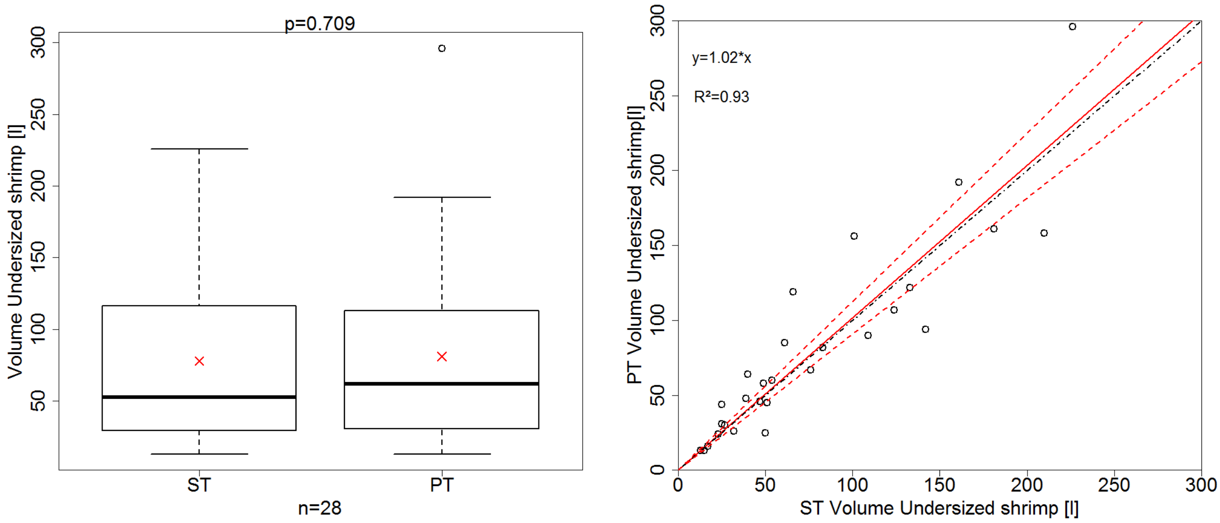



**Figure 39: Share of the three fractions shrimp (darkblue), by-catch (red) and the remainder (grey) in the total catch for standard trawl (ST) and pulse trawl (PT).**

The only fraction that has not been considered is the undersized shrimp fraction sorted out in the rotary sieve.

### 3.3.1.4 Undersized shrimp

**(A)**




**(B)**

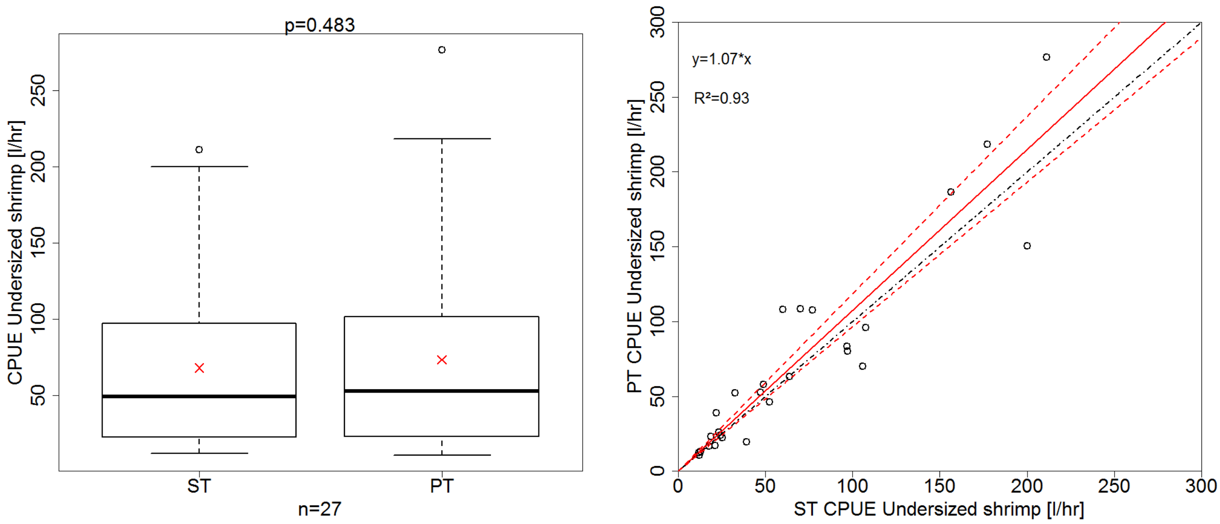



**Figure 40: Comparison of the undersized shrimp for standard trawl (ST) and pulse trawl (PT) (A) Absolute undersized shrimp volume, (B) undersized shrimp as CPUE (l/h) during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

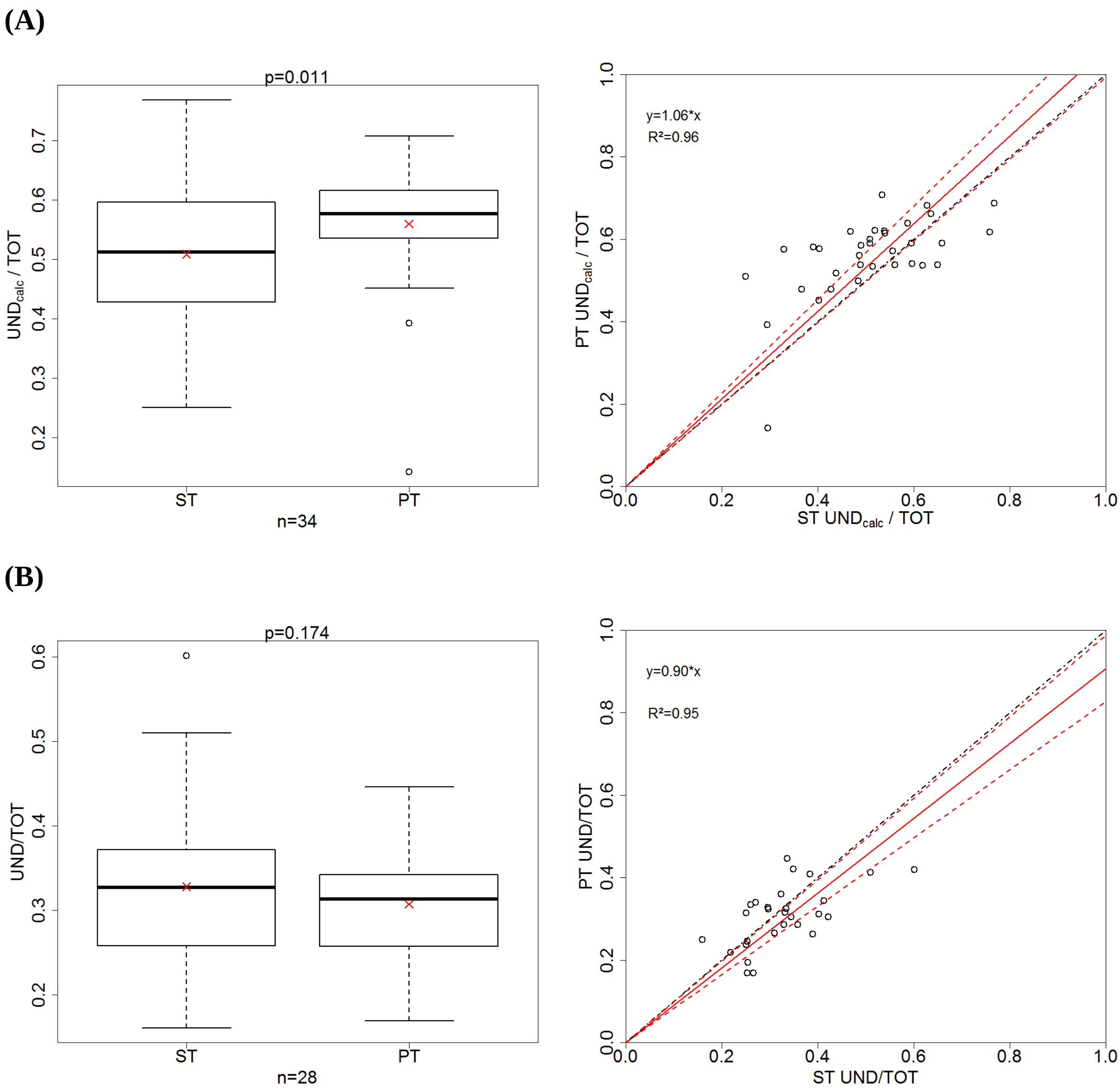



**Figure 41: Comparison of two ratios comprising undersized shrimp for standard trawl (ST) and pulse trawl (PT). (A) Ratio between calculated undersized shrimp and total catch ratio (B) Ratio between measured undersized shrimp and total catch, during the scientific-sampling phase. The means are marked as red crosses. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

The Wilcoxon Test and the linear model reveal that there is no difference between the standard and the pulse gear in terms of the absolute volume and the CPUE of undersized shrimp. There is a discrepancy between the calculated and the measured undersized shrimp in relation to the total catch. While the calculated undersized shrimp show a significant difference between the gears, the measured undersized shrimp do not, when the Wilcoxon Test is considered. The linear regression states the opposite: no difference when the calculated undersized shrimp fractions are compared and a significant difference of the slope from 1 when considering the measured fraction.

### 3.3.2 Effect of parameters on the catch

Since the catchability of shrimp may depend on a variety of factors, a number of parameters were tested during the scientific-sampling:

1. Salinity
2. Towing speed
3. Fishing without pulses

Additionally, the influence of light was evaluated during the self-sampling (Chapter 3.2.2).

#### 3.3.2.1 Salinity

The data regarding different salinities was evaluated in the same way as the day-twilight-night comparison in Chapter 3.2.2, i.e. the percentage of the share of the pulse gear in the individual fractions was compared to the share of the standard gear. When regular and low salinities were compared, the Wilcoxon Rank Sum Test for independent samples was used. The comparison of the gears at the same salinity made the application of the Wilcoxon Sign Rank Test possible, as the gears fished the same population simultaneously.

a) Total catch

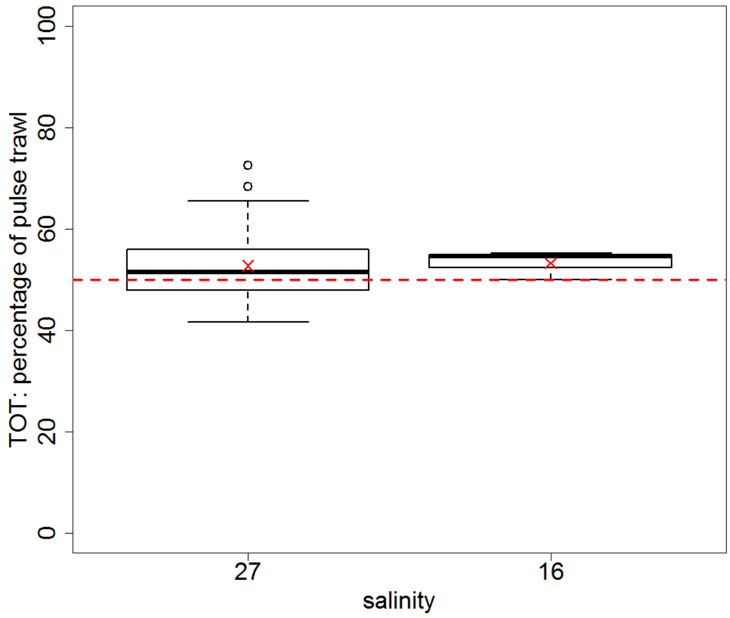



**Figure 42: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for total catch (TOT) at different salinities. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 17: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding the salinity for total catch. Significant differences are marked with an asterisk.**

| | $PT_{27}$ n=32 | $PT_{16}$ n=3 | $ST_{27}$ n=32 | $ST_{16}$ n=3 |
|---|---|---|---|---|
| $PT_{27}$ | | | | |
| $PT_{16}$ | 0.8593 | | | |
| $ST_{27}$ | 0.06431 | 0.09811 | | |
| $ST_{16}$ | 0.09811 | 0.3711 | 0.8593 | |

The Wilcoxon Test applied on the data sets comparing the total catch in different salinities revealed no difference between the gears. There is neither a difference between both gears at the same salinity nor when they are compared within themselves at different salinities.

b) By-catch

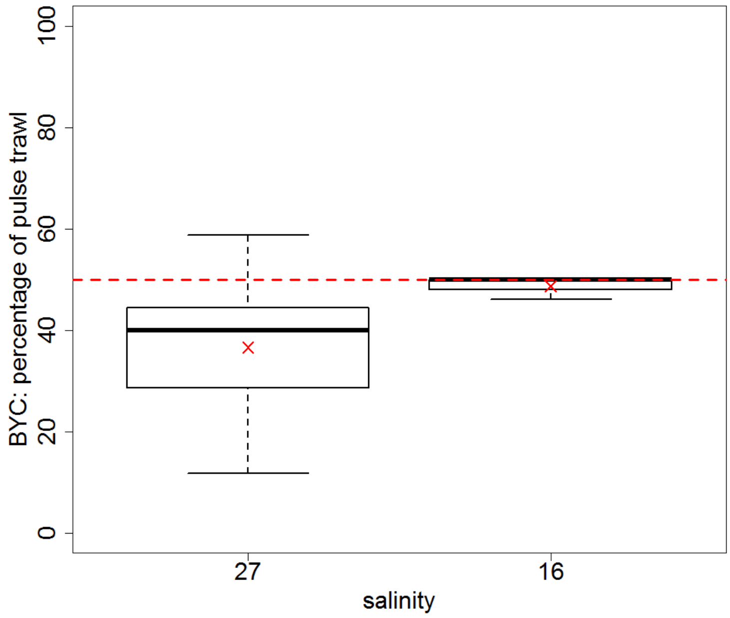



**Figure 43: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for by-catch (BYC) at different salinities. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross**

**Table 18: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding the salinity for the by-catch. Significant differences are marked with an asterisk.**

| | $PT_{27}$ n=32 | $PT_{16}$ n=3 | $ST_{27}$ n=31 | $ST_{16}$ n=3 |
|---|---|---|---|---|
| $PT_{27}$ | | | | |
| $PT_{16}$ | 0.04479* | | | |
| $ST_{27}$ | 1.607e-05* | 0.0286* | | |
| $ST_{16}$ | 0.0286* | 1 | 0.04479* | |

As the salinity drops, the shares of HOVERCRAN and standard gear equalize. The hauls in the Elbe estuary show no difference in share of overall by-catch between standard and pulse gear. The results of comparing the gears at a low salinity are coherent with the comparison of the gears within themselves. The pulse gear's share rises, while the standard gear's share declines as the salinity drops to 16. This results in significant differences within the gears when comparing the two salinities. The reasons for this behavior are unclear.

c) Shrimp fraction

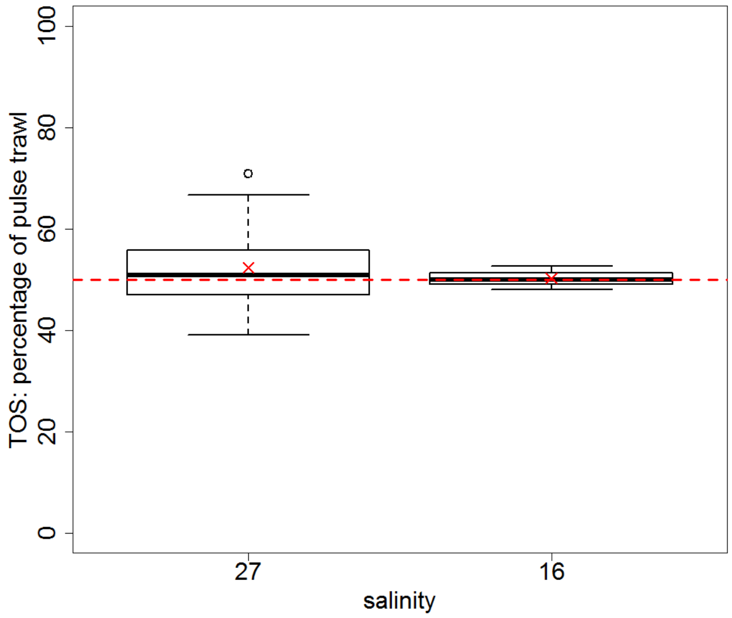



**Figure 44: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for shrimp fraction (TOS) at different salinities. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 19: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding the salinity for the shrimp fraction. Significant differences are marked with an asterisk.**

| | $PT_{27}$ n=32 | $PT_{16}$ n=3 | $ST_{27}$ n=32 | $ST_{16}$ n=3 |
|---|---|---|---|---|
| $PT_{27}$ | | | | |
| $PT_{16}$ | 0.7455 | | | |
| $ST_{27}$ | 0.1513 | 0.7013 | | |
| $ST_{16}$ | 0.7013 | 1 | 0.7455 | |

The performance of the pulse and the standard gear is equal regarding the shrimp fraction, independent from the salinity. There is no significant difference, neither between the gears at a salinity of 16 nor when comparing the gears within themselves under regular and low salinity conditions.

d) Undersized shrimp

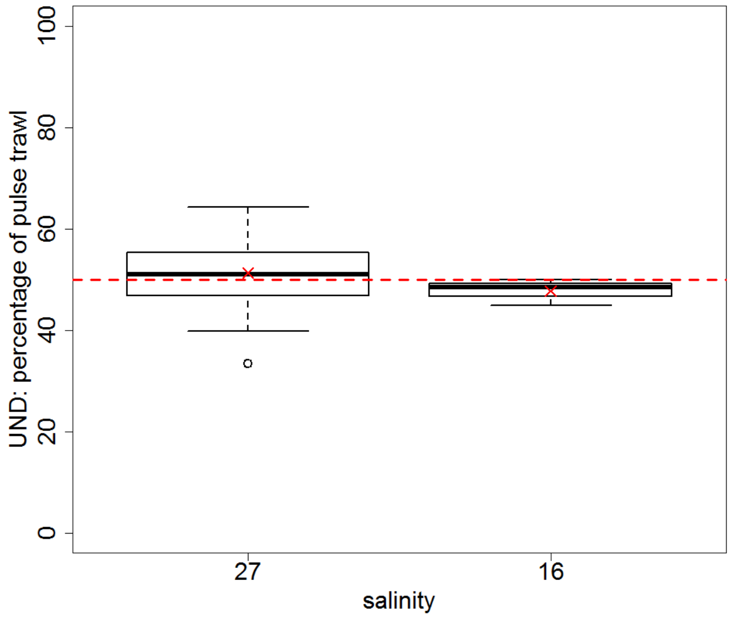



**Figure 45: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for undersized shrimp (UND) at different salinities. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 20: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding the salinity for the undersized shrimp. Significant differences are marked with an asterisk.**

| | $PT_{27}$ n=25 | $PT_{16}$ n=3 | $ST_{27}$ n=25 | $ST_{16}$ n=3 |
|---|---|---|---|---|
| $PT_{27}$ | | | | |
| $PT_{16}$ | 0.3727 | | | |
| $ST_{27}$ | 0.3746 | 0.7381 | | |
| $ST_{16}$ | 0.7381 | 0.3711 | 0.3727 | |

The comparison of pulse and standard gear at different salinities results in a non-significant difference between the gears, concerning the undersized shrimp fraction. No difference can be observed when comparing the gears within themselves at low and regular salinity, and no difference is to be seen when the gears are compared with each other at the same salinity, be it regular or low.

### 3.3.2.2 Towing speed

Several hauls were conducted at three different speeds. The regular towing speed in shrimp trawling is approximately 3kn. Hauls were conducted at 2.5kn, 3kn and 3.5kn.

a) Total catch

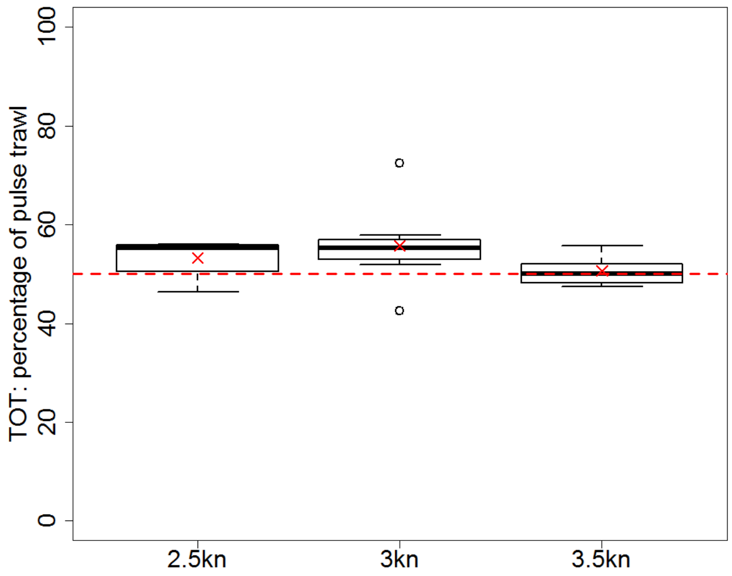



**Figure 46: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for total catch (TOT) at different towing speeds. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 21: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding different towing speeds for the total catch. Significant differences are marked with an asterisk.**

| | $PT_{v\sim2.5kn}$ n=4 | $PT_{v\sim3kn}$ n=7 | $PT_{v\sim3.5kn}$ n=5 | $ST_{v\sim2.5kn}$ n=4 | $ST_{v\sim3kn}$ n=7 | $ST_{v\sim3.5kn}$ n=5 |
|---|---|---|---|---|---|---|
| $PT_{v\sim2.5kn}$ | | | | | | |
| $PT_{v\sim3kn}$ | 0.9273 | | | | | |
| $PT_{v\sim3.5kn}$ | 0.4127 | 0.202 | | | | |
| $ST_{v\sim2.5kn}$ | 0.25 | 0.1091 | 0.1905 | | | |
| $ST_{v\sim3kn}$ | 0.1091 | 0.1563 | 0.07323 | 0.9273 | | |
| $ST_{v\sim3.5kn}$ | 0.1905 | 0.07323 | 0.8551 | 0.4127 | 0.202 | |

There is no significant difference, neither between the gears nor within the gears, for every speed that was tested. In other words, the gears perform in the same way, regardless of the speed.

b) By-catch

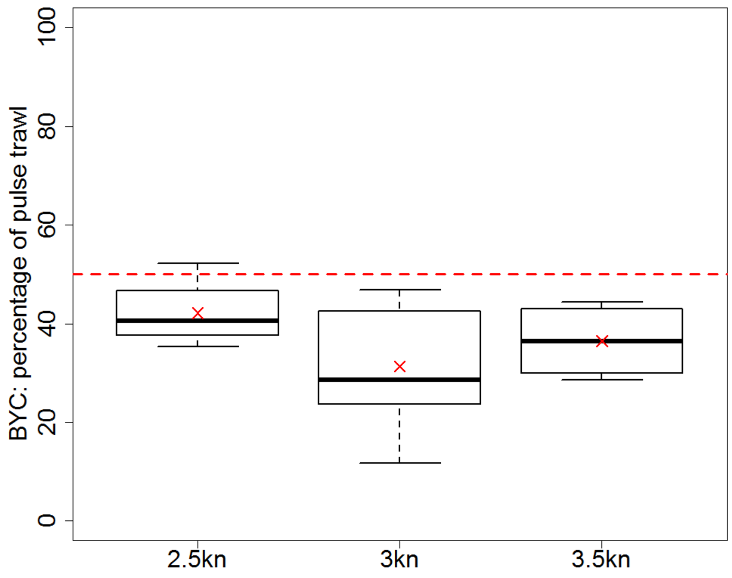



**Figure 47: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for by-catch (BYC) at different towing speeds. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 22: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding different towing speeds for the by-catch. Significant differences are marked with an asterisk.**

| | $PT_{v\sim2.5kn}$ n=4 | $PT_{v\sim3kn}$ n=7 | $PT_{v\sim3.5kn}$ n=5 | $ST_{v\sim2.5kn}$ n=4 | $ST_{v\sim3kn}$ n=7 | $ST_{v\sim3.5kn}$ n=4 |
|---|---|---|---|---|---|---|
| $PT_{v\sim2.5kn}$ | | | | | | |
| $PT_{v\sim3kn}$ | 0.3152 | | | | | |
| $PT_{v\sim3.5kn}$ | 0.6857 | 0.5064 | | | | |
| $ST_{v\sim2.5kn}$ | 0.25 | 0.006061* | 0.02857* | | | |
| $ST_{v\sim3kn}$ | 0.006061* | 0.01563* | 0.006061* | 0.3152 | | |
| $ST_{v\sim3.5kn}$ | 0.02857* | 0.006061* | 0.125 | 0.6857 | 0.5064 | |

Only when the vessel is towing at regular speed a significant difference between the gears was found concerning the by-catch fraction. In contrast to this observation, no significant difference is detectable when comparing the gears within themselves at different speeds. The lacking difference between the gears becomes only visible when the gears are compared directly. This may be attributed to the low number of hauls. The variance within the groups may be too high to produce a convincing result. This is supported by the statement gained from Figure 48.

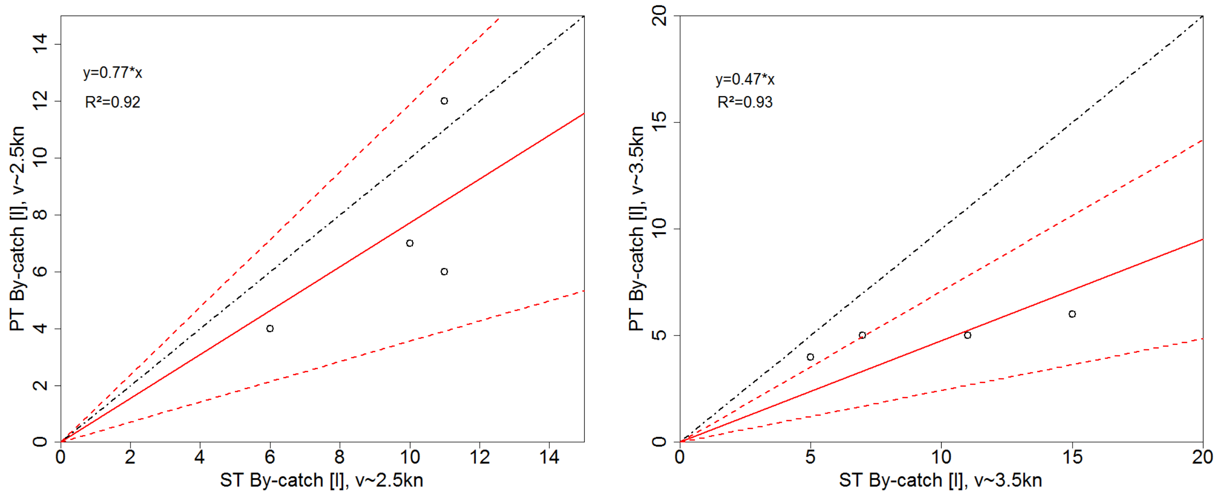



**Figure 48: Comparison of standard trawl (ST) and pulse trawl (PT) at different towing speeds regarding by-catch. (A) v~2.5kn, (B) v~3.5kn. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half.**

Even though the Wilcoxon Test states a non-significant difference between standard and pulse gear, the linear regression for low speed is inclined towards the standard gear. However, the slope does not differ significantly from 1 and the true value may be in a large interval.

The linear regression of the data collected at high speed shows that more by-catch is produced using the standard gear, as the slope is significantly lower than 1. This is set in contrast to the statement of the Wilcoxon Test.

c) Shrimp fraction

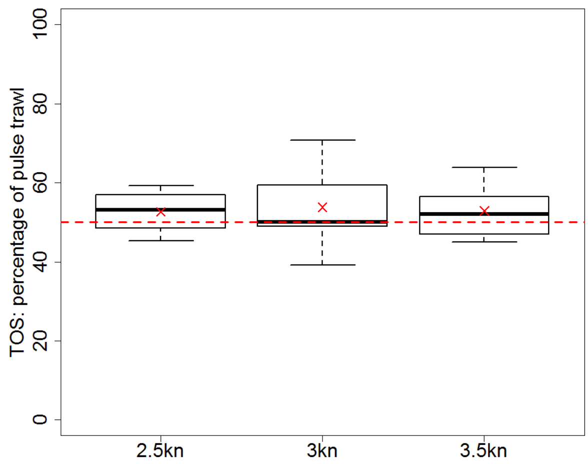



**Figure 49: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for shrimp fraction (TOS) at different towing speeds. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 23: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding different towing speeds for the shrimp fraction. Significant differences are marked with an asterisk.**

| | $PT_{v\sim2.5kn}$ n=4 | $PT_{v\sim3kn}$ n=7 | $PT_{v\sim3.5kn}$ n=5 | $ST_{v\sim2.5kn}$ n=4 | $ST_{v\sim3kn}$ n=7 | $ST_{v\sim3.5kn}$ n=5 |
|---|---|---|---|---|---|---|
| $PT_{v\sim2.5kn}$ | | | | | | |
| $PT_{v\sim3kn}$ | 0.9273 | | | | | |
| $PT_{v\sim3.5kn}$ | 1 | 0.8763 | | | | |
| $ST_{v\sim2.5kn}$ | 0.625 | 0.3152 | 0.4127 | | | |
| $ST_{v\sim3kn}$ | 0.3152 | 0.5294 | 0.3709 | 0.9273 | | |
| $ST_{v\sim3.5kn}$ | 0.4127 | 0.3709 | 0.625 | 1 | 0.8763 | |

There is no difference between the two gears at any speed when considering the shrimp fraction. Both gears perform equally well at all three towing speeds.

d) Undersized shrimp

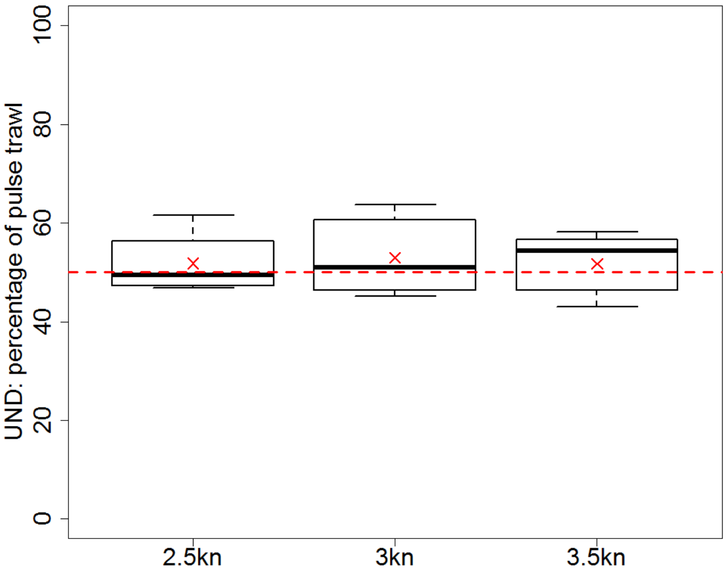



**Figure 50: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for undersized shrimp (UND) at different towing speeds. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 24: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) regarding different towing speeds for the undersized shrimp. Significant differences are marked with an asterisk.**

| | $PT_{v\sim2.5kn}$ n=4 | $PT_{v\sim3kn}$ n=7 | $PT_{v\sim3.5kn}$ n=5 | $ST_{v\sim2.5kn}$ n=4 | $ST_{v\sim3kn}$ n=7 | $ST_{v\sim3.5kn}$ n=5 |
|---|---|---|---|---|---|---|
| $PT_{v\sim2.5kn}$ | | | | | | |
| $PT_{v\sim3kn}$ | 1 | | | | | |
| $PT_{v\sim3.5kn}$ | 0.9048 | 0.9307 | | | | |
| $ST_{v\sim2.5kn}$ | 1 | 0.6095 | 0.4127 | | | |
| $ST_{v\sim3kn}$ | 0.6095 | 0.6875 | 0.329 | 1 | | |
| $ST_{v\sim3.5kn}$ | 0.4127 | 0.329 | 0.625 | 0.9048 | 0.9307 | |

The difference regarding the undersized shrimp is non-significant between the standard and the pulse gear. At any given towing speed the gears showed the same performance.

3.3.2.3 No pulse

The purpose of fishing with the pulse gear switched off is to detect the effect of the bobbin rope and the according netting on the pulse system. Thus, it can also be evaluated whether the pulses serve their purpose of startling the shrimp or whether the startle response is triggered by the bobbin rope.

a) Total catch

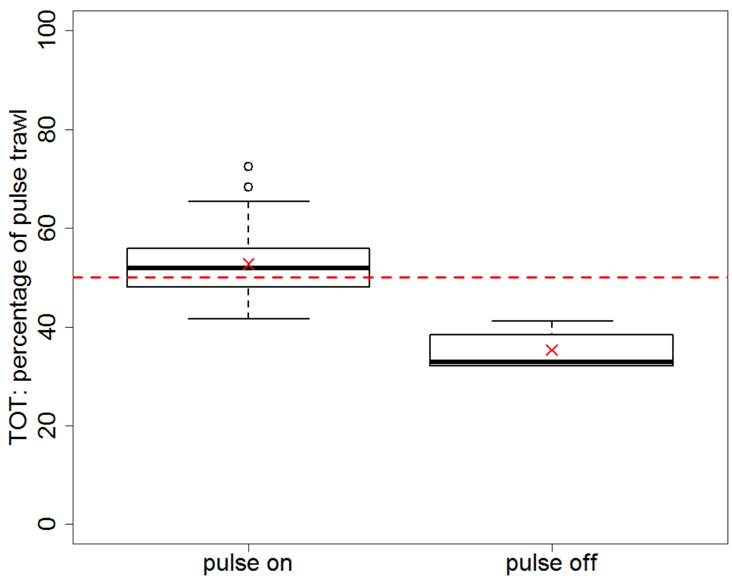



**Figure 51: Percentage of the volume caught using the HOVERCRAN in relation to overall volume (volume ST + volume PT) for total catch (TOT) without pulses. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 25: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) without pulses for the total catch. Significant differences are marked with an asterisk.**

| | $PT_{on}$ n=35 | $PT_{off}$ n=5 | $ST_{PT\_on}$ n=35 | $ST_{PT\_off}$ n=5 |
|---|---|---|---|---|
| $PT_{on}$ | | | | |
| $PT_{off}$ | 0.0003653* | | | |
| $ST_{PT\_on}$ | 0.03317* | 0.002434* | | |
| $ST_{PT\_off}$ | 0.002434* | 0.0625 | 0.0003653* | |

The Wilcoxon Test shows a significant difference between the hauls with and the hauls without pulses. The p-values also show a significant difference when the gears are compared with the HOVERCRAN switched on. This opposes to the results obtained in Chapter 3.3.1.1

where no difference between the two gears under regular conditions could be found. However, in the respective chapter, the absolute volumes were tested. It seems, as there is no significant difference between the gears, once the pulses are switched off. This suggests that the gears have an equal share in the volume of the overall total catch. This test result is to be handled with care, as all values of the HOVERCRAN's share in the overall total catch lie beneath the 50% mark. Because of this, a linear regression model comparing the two gears with the pulse gear in off-mode is established in Figure 52.

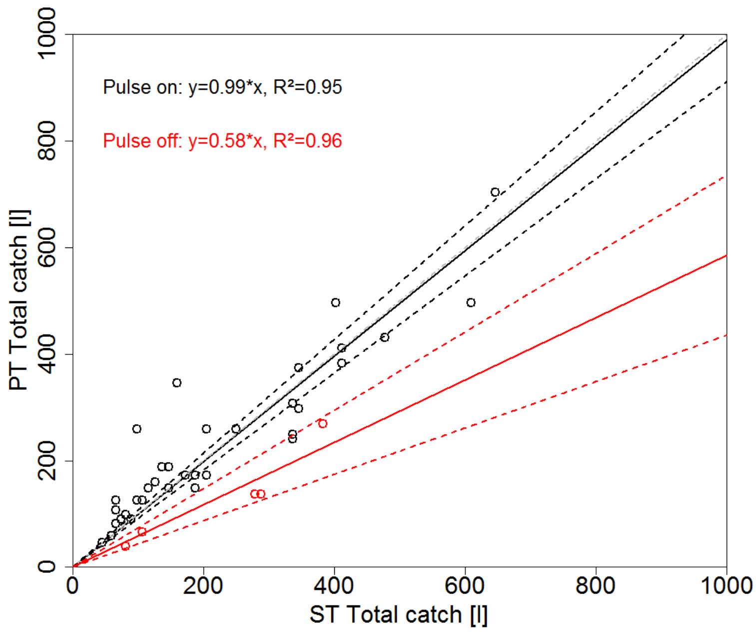



**Figure 52: Comparison of standard trawl (ST) and pulse trawl (PT) regarding the volume of total catch (TOT). The solid lines are the linear regression with the according confidence intervals (dashed lines). The identity line is depicted as grey dashed-dotted line splitting the plot in half. The colors mark whether the pulse gear is turned on (black) or turned off (red).**

The linear regression model applied to the volumes of the total catch shows that, in contrast to the statement above, there is a difference between the standard and the pulse gear when the pulses are not active. The slope is significantly different from 1. The contradiction between the linear regression model and the Wilcoxon Test may be attributed to too few data sets to reveal significant results in the Wilcoxon Test.

b) By-catch

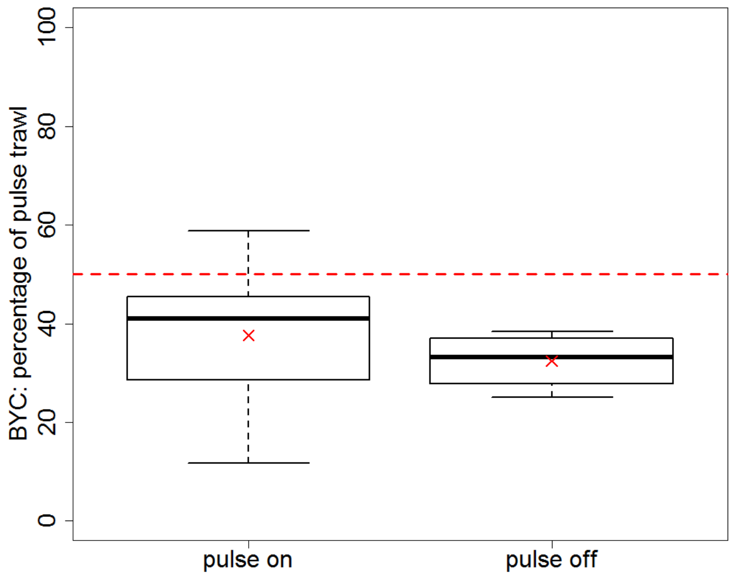



**Figure 53: Percentage of the volume caught using the HOVERCRAN in relation to the overall volume (volume ST + volume PT) for by-catch (BYC) without pulses. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 26: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) without pulses for the by-catch. Significant differences are marked with an asterisk.**

| | $PT_{on}$ n=35 | $PT_{off}$ n=5 | $ST_{PT\_on}$ n=34 | $ST_{PT\_off}$ n=4 |
|---|---|---|---|---|
| $PT_{on}$ | | | | |
| $PT_{off}$ | 0.3289 | | | |
| $ST_{PT\_on}$ | 1.2e-05* | 0.001309* | | |
| $ST_{PT\_off}$ | 0.001309* | 0.125 | 0.3289 | |

The comparison of the pulse gear with the HOVERCRAN switched off to the pulse gear with the HOVERCRAN switched on and the respective comparison in the standard gear shows no significant difference between the two modes. This means, that theoretically the significant difference visible between the standard and the pulse gear under regular conditions (Figure 35) should also be observable when the pulse gear is switched off. The Wilcoxon Test shows, however, no significant difference. This unclear result can be investigated further through the application of a linear regression model to the absolute volume data sets (Figure 54).

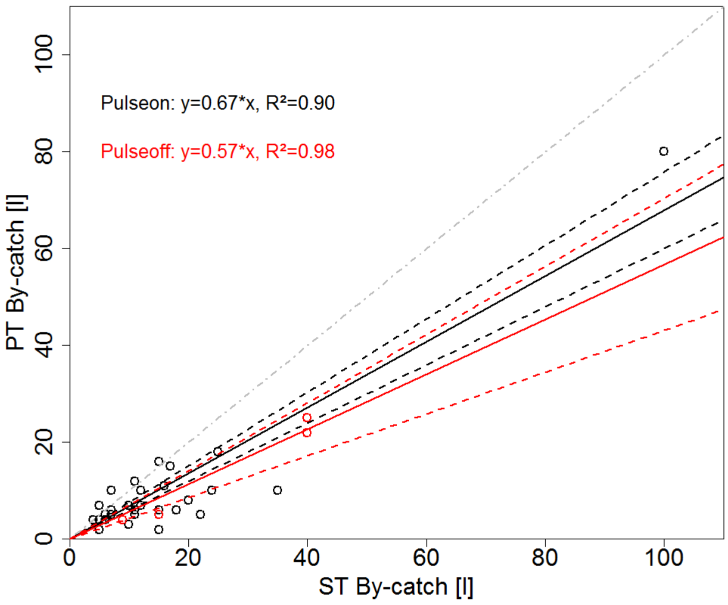



**Figure 54: Comparison of standard trawl (ST) and pulse trawl (PT) regarding the by-catch. The solid lines are the linear regression with the according confidence intervals (dashed lines). The identity line is depicted as the grey dashed-dotted line splitting the plot in half. The colors mark whether the pulse gear is turned on (black) or turned off (red). The colors mark whether the pulse gear is turned on (black) or turned off (red).**

The linear regression shows comparable behavior of the gears regardless whether the pulses are active or not. This is in direct contrast to the test result in Table 26, where no difference between the standard and pulse trawl without pulses was stated.

As the linear model states a significant by-catch reduction when using the HOVERCRAN, regardless of the pulse status, compared to the standard trawl, it can be stated that the modified bobbin rope is working properly. A scaring effect of the electric field can be ruled out as a cause for a reduction of by-catch since the same results are achieved with and without pulses. On the contrary, since there is even less by-catch in the HOVERCRAN catch without pulses, a startling effect of the electric field on fish is possible.

c) Shrimp fraction

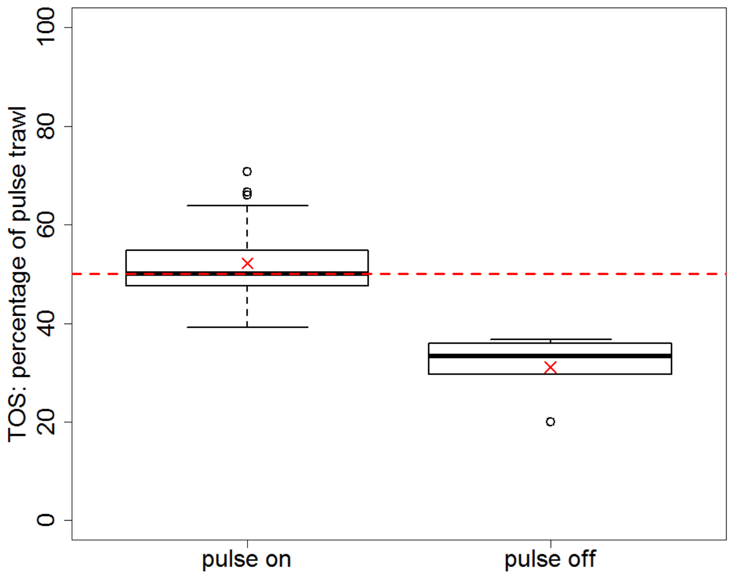



**Figure 55: Percentage of the volume caught using the HOVERCRAN of overall volume (volume ST + volume PT) for shrimp fraction (TOS) without pulses. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 27: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) without pulses for the shrimp fraction. Significant differences are marked with an asterisk.**

| | $PT_{on}$ n=35 | $PT_{off}$ n=5 | $ST_{PT\_on}$ n=35 | $ST_{PT\_off}$ n=5 |
|---|---|---|---|---|
| $PT_{on}$ | | | | |
| $PT_{off}$ | 0.0003686* | | | |
| $ST_{PT\_on}$ | 0.1588 | 0.001509* | | |
| $ST_{PT\_off}$ | 0.001509* | 0.0625 | 0.0003686* | |

As in the previous chapters, there is no difference between the performance of the gears when the pulses are switched on. There is also no difference between the gears when the pulses are switched off. Due to the low number of hauls, this result is to be handled with care, since all values of the pulse gear's share in the overall shrimp fraction lie below 40%. Additionally, there is a difference between the pulse gear's share with the pulses on compared to the pulses off. Under regular conditions there is no difference between the gears, thus there should be a difference between the gears without pulses. Figure 56 illustrates this in a linear regression.

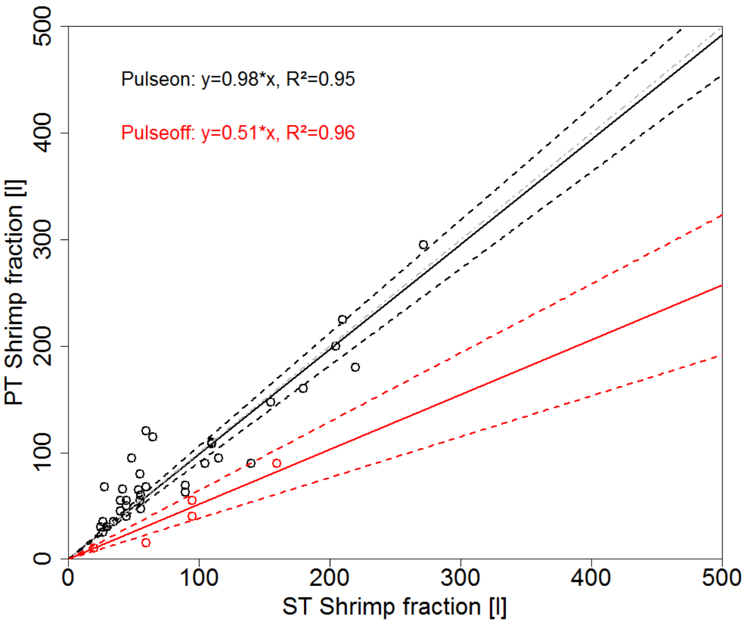



**Figure 56: Comparison of standard trawl (ST) and pulse trawl (PT) regarding the volume of the shrimp fraction. The solid lines are the linear regression with the according confidence intervals (dashed lines). The identity line is depicted as the grey dashed-dotted line splitting the plot in half. The colors mark whether the pulse gear is turned on (black) or turned off (red). The colors mark whether the pulse gear is turned on (black) or turned off (red).**

Though the Wilcoxon Test shows no significant difference between the gears when the HOVERCRAN is turned off, the linear regression model of the data is stating the contrary. The slope comparing the volumes is inclined to the standard gear with a significant difference from 1. As a result, the share of pulse and standard gear should not be equal.

The results from the comparison of the share of the pulse gear switched on to the pulse gear switched off and the linear regression are stating that the pulses serve their purpose: startling shrimp.

d) Undersized shrimp

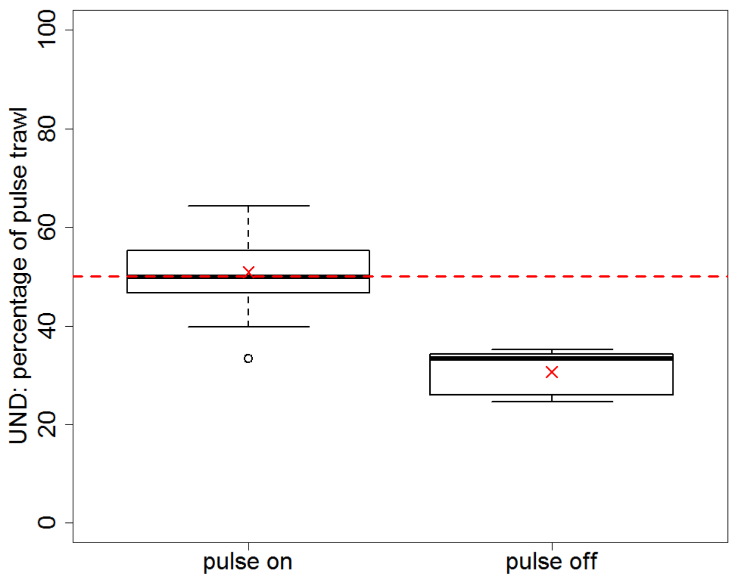



**Figure 57: Percentage of the volume caught using the HOVERCRAN of overall volume (volume ST + volume PT) for undersized shrimp (UND) without pulses. The equilibrium between both gears (50%) is marked as red dashed line. The mean is marked as a red cross.**

**Table 28: Results of the Wilcoxon Test comparing of the share of the pulse trawl (PT) to the share of the standard trawl (ST) without pulses for the undersized shrimp. Significant differences are marked with an asterisk.**

| | $PT_{on}$ n=28 | $PT_{off}$ n=5 | $ST_{PT\_on}$ n=28 | $ST_{PT\_off}$ n=5 |
|---|---|---|---|---|
| $PT_{on}$ | | | | |
| $PT_{off}$ | 0.0007665* | | | |
| $ST_{PT\_on}$ | 0.5322 | 0.0004833* | | |
| $ST_{PT\_off}$ | 0.0004833* | 0.0625 | 0.0007665* | |

The comparison within the gears shows a significant difference between the pulse gear in on and in off-mode, when considering the undersized shrimp. Yet, there is no difference to be stated when the gears are compared to one another. There is no significant difference between the gears, neither when the HOVERCRAN is switched on, nor when it is switched off. All values of the HOVERCRAN's share in the overall undersized shrimp catch lie below the 40% mark and a significant difference within the gears is present, therefore the lacking difference between the gears needs to be investigated further. For clarification, the linear regression model is applied to the volume data sets and depicted in Figure 58.

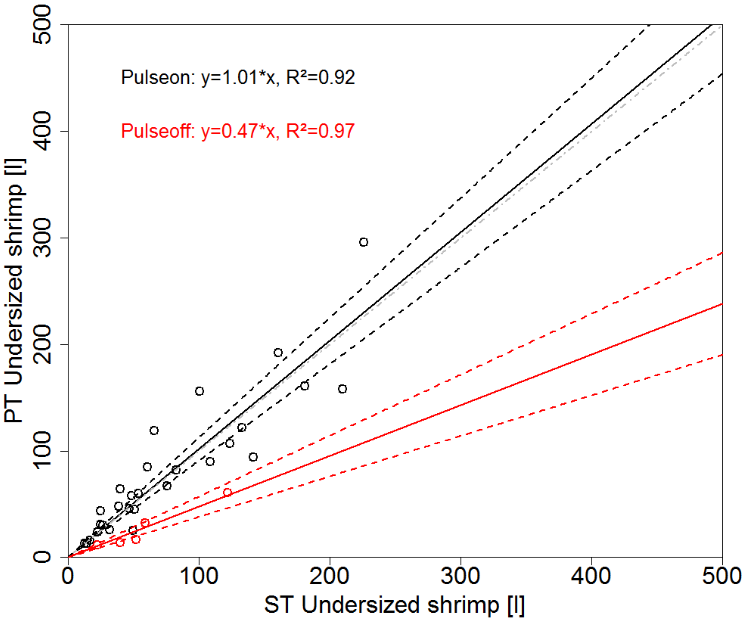



**Figure 58: Comparison of standard trawl (ST) and pulse trawl (PT) regarding the undersized shrimp. The solid lines are the linear regression with the according confidence intervals (dashed lines). The identity line is depicted as the grey dashed-dotted line splitting the plot in half. The colors mark whether the pulse gear is turned on (black) or turned off (red). The colors mark whether the pulse gear is turned on (black) or turned off (red).**

The results of the linear regression do not correlate with the Wilcoxon Test. The regression slope shows a significant difference from 1, opposing to the statement of equal shares of both gears. A definite inclination towards the standard gear can be observed when the pulses are not active.

### 3.3.3 Analysis of by-catch

The composition of the by-catch with respect to species and length classes is analyzed in this section. On the one hand, the fraction of by-catch sorted out by the rotary sieve is evaluated and on the other hand the fish in the shrimp fraction, previously referred to "extra-fish" (Figure 8), is also subject to analysis.

<u>3.3.3.1 By-catch fraction</u>

A total of 29 species were present overall, 27 of which were observed in the by-catch obtained with the pulse gear and 27 in the by-catch obtained with the standard gear. Table 29 gives an overview on presence in the hauls and the number of individuals. The percentages indicate in how many hauls the concerned species was recorded.

**Table 29: Presence of species and number of individuals, sorted by standard trawl (ST) and pulse trawl (PT). The index indicates whether the pulse gear had been switched on.**

| | | Presence | | | | Number of individuals | | | |
|---|---|---|---|---|---|---|---|---|---|
| | species | ST | PT | $ST_{off}$ | $PT_{off}$ | ST | PT | $ST_{off}$ | $PT_{off}$ |
| flatfish | *Limanda limanda* | 51.52% | 55.88% | 20% | 40% | 227 | 115 | 1 | 27 |
| flatfish | *Microstomus kitt* | 6.06% | 2.94% | 0% | 0% | 10 | 2 | 0 | 0 |
| flatfish | *Psetta maxima* | 9.09% | 0% | 0% | 0% | 3 | 0 | 0 | 0 |
| flatfish | *Scophthalmus rhombus* | 0% | 2.94% | 0% | 20% | 0 | 1 | 0 | 1 |
| flatfish; Commercial species | *Pleuronectes platessa* | 100% | 100% | 100% | 100% | 12141 | 8726 | 2932 | 2045 |
| flatfish; Commercial species | *Solea solea* | 100% | 94.12% | 100% | 80% | 2677 | 1528 | 218 | 149 |
| flatfish; Commercial species | *Platichthys flesus* | 66.67% | 29.41% | 100% | 20% | 92 | 91 | 26 | 1 |
| Commercial species | *Gadus morhua* | 33.33% | 11.76% | 40% | 40% | 17 | 6 | 2 | 5 |
| Commercial species | *Merlangius merlangus* | 66.67% | 64.71% | 100% | 80% | 115 | 127 | 57 | 14 |
| Commercial species | *Clupea harengus* | 96.97% | 100% | 100% | 100% | 6677 | 3702 | 400 | 716 |
| Commercial species | *Sprattus sprattus* | 69.7% | 58.82% | 100% | 80% | 175 | 220 | 55 | 66 |
| | *Osmerus eperlanus* | 100% | 100% | 100% | 100% | 9792 | 10363 | 2745 | 2135 |

| species | ST | PT | $ST_{off}$ | $PT_{off}$ | ST | PT | $ST_{off}$ | $PT_{off}$ |
|---|---|---|---|---|---|---|---|---|
| *Alosa fallax* | 63.64% | 58.82% | 80% | 80% | 66 | 112 | 18 | 46 |
| *Liparis liparis* | 72.73% | 79.41% | 100% | 60% | 369 | 296 | 134 | 25 |
| *Syngnathus rostrellatus* | 78.79% | 79.41% | 100% | 80% | 1380 | 760 | 182 | 283 |
| *Pomatoschistus minutus* | *72.73%* | *67.65%* | *100%* | *60%* | *2355* | *531* | *260* | *53* |
| *Ciliata mustela* | 54.55% | 50% | 80% | 60% | 61 | 57 | 23 | 15 |
| *Pholis gunnellus* | 57.58% | 47.06% | 60% | 60% | 60 | 57 | 23 | 11 |
| *Ammodytes tobianus* | 18.18% | 35.29% | 60% | 60% | 13 | 53 | 8 | 29 |
| *Agonus cataphractus* | 57.58% | 32.35% | 100% | 20% | 159 | 44 | 29 | 1 |
| *Lampetra fluviatilis* | 18.18% | 20.59% | 80% | 80% | 19 | 19 | 5 | 10 |
| *Myxocephalus scorpius* | 30.3% | 20.59% | 60% | 20% | 23 | 17 | 5 | 1 |
| *Zoareces viviparus* | 18.18% | 17.65% | 80% | 80% | 15 | 18 | 16 | 8 |
| *Scombrus scombrus* | 18.18% | 8.82% | 0% | 0% | 9 | 5 | 0 | 0 |
| *Trachurus trachurus* | 0% | 8.82% | 0% | 0% | 0 | 3 | 0 | 0 |
| *Callionymus lyra* | 6.06% | 5.88% | 0% | 0% | 2 | 12 | 0 | 0 |
| *Chelidonichtys lucerna* | 6.06% | 5.88% | 0% | 20% | 2 | 3 | 0 | 3 |
| *Belone belone* | 3.03% | 2.94% | 0% | 0% | 1 | 1 | 0 | 0 |
| *Gasterosteus aculeatus* | 3.03% | 0% | 0% | 0% | 1 | 0 | 0 | 0 |
| **Sum** | | | | | 36461 | 26869 | 7139 | 5642 |

During the regular operation of the pulse gear, most species are caught equally frequent with both gears. Considerable differences can be seen in flounder (*P. flesus*), as this species was caught half as often with the pulse gear as with the standard gear. However, almost the same number of individuals was caught. Half as many herring (*C. harengus*) were caught using the HOVERCRAN and 42% less sole (*S. solea*). For plaice (*P. platessa*) a 30% catch reduction is visible with the new system.

The comparison of hauls without any pulses has a similar outcome, except for flounder, where the reduction cannot only be seen in the frequency, but also in the number of individuals caught. Fewer sole and plaice were found in the by-catch obtained with the pulse gear. Interestingly, the number of herring caught with the HOVERCRAN was double the number caught with the standard gear. Since the design and background of the straight bobbin rope is to improve flight chances for flatfish and other demersal species (Chapter 2.2.1), this inconsistency is of minor relevance.

a) Weight distribution

Figure 59 compares the share of the pulse gear in the overall weight of the frequently observed flatfish, while Figure 61 deals with the commercial roundfish. Additionally, the significance test Wilcoxon Sign Rank Test was carried out for each species. Also, a linear model was applied to the data and evaluated. The results are shown in Figure 60 and Figure 62.

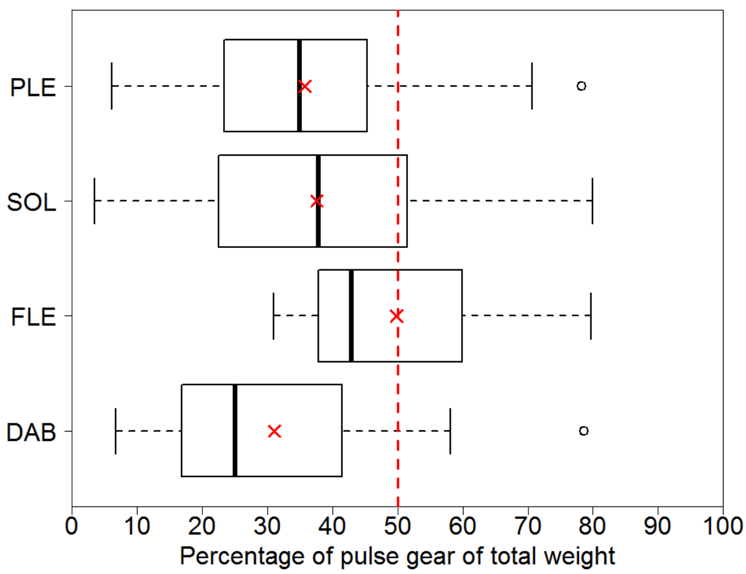
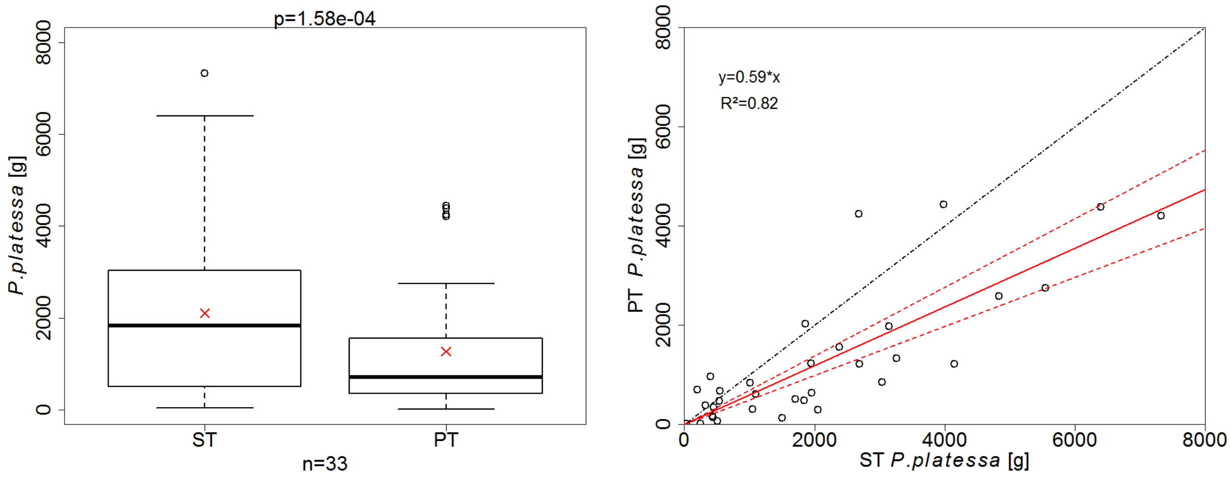


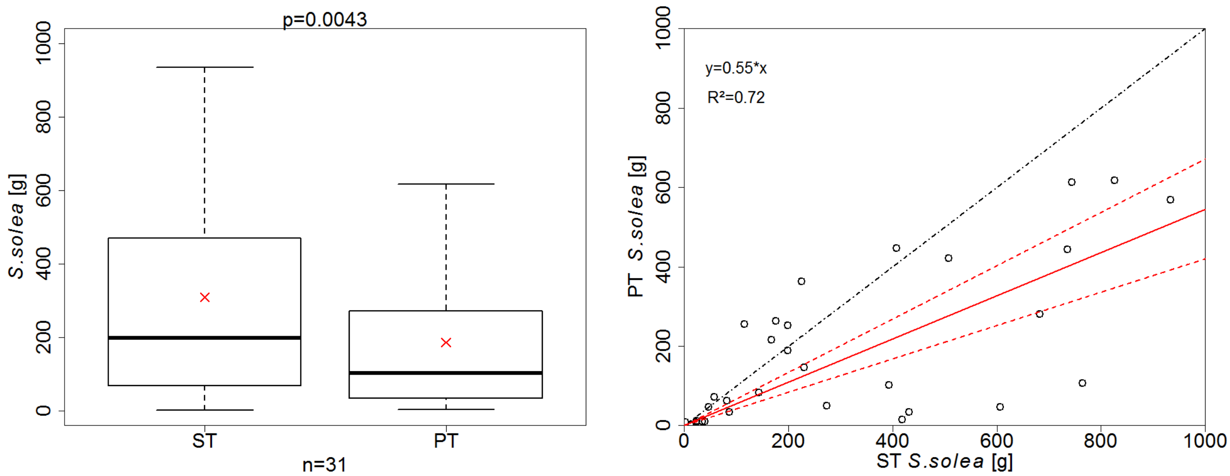

**Figure 59: Comparison of share of pulse trawl in overall weight of flatfish: *P. platessa* (PLE), *S. solea* (SOL), *P. flesus* (FLE), *L. limanda* (DAB)**

The minor share of the HOVERCRAN gear applies to all species, except flounder. The median and mean in the case of flounder differ, as the higher values are almost double of the lower values. All lower values are approximately in the same range and the high values have great impact on the mean.

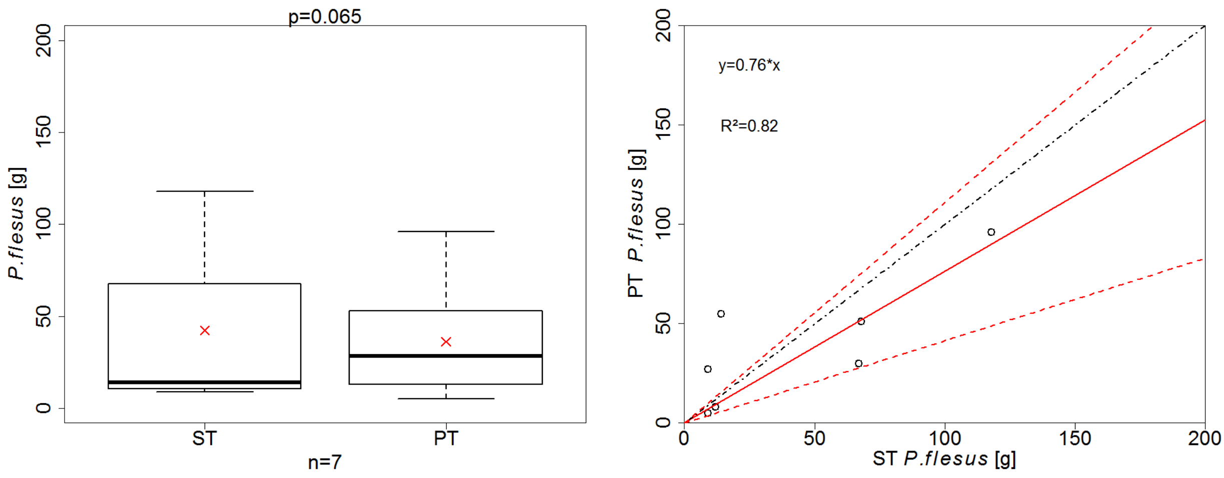
**(A)**




**(B)**



**(C)**




**(D)**

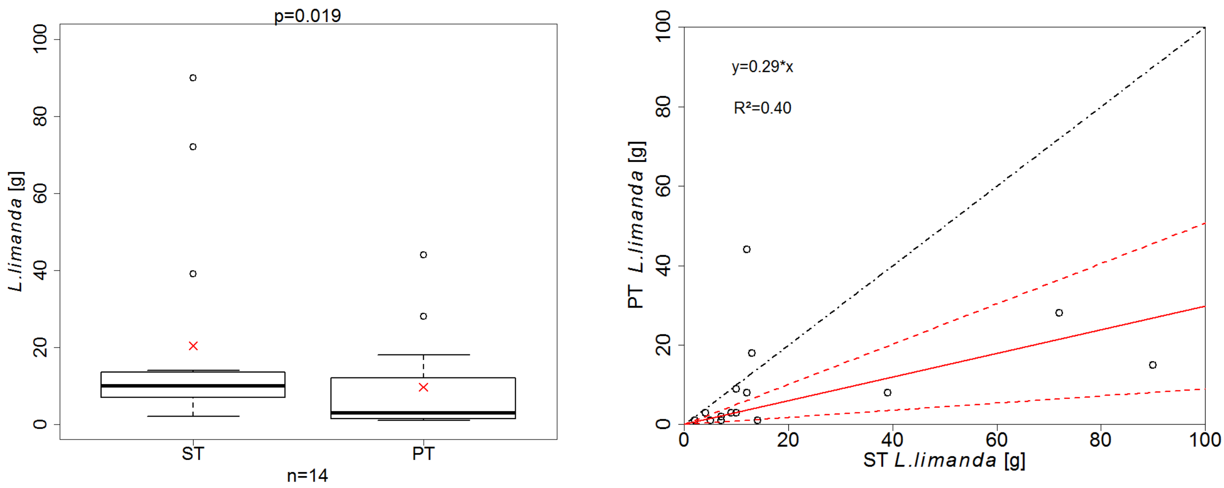



**Figure 60: Comparison of the weights of flatfish according to standard trawl (ST) and pulse trawl (PT). (A) *P. platessa*, (B) *S. solea*, (C) *P. flesus*, (D) *L. Limanda.* The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

Figure 60 confirms what Figure 59 suggested. The difference between the gears regarding weight is significant for all species, except flounder. The significance is on the one hand indicated by the small p-values obtained using the Wilcoxon Test, on the other hand through the slope of the linear regression. All slopes were tested whether they differ significantly from 1 and for all, except flounder, p-values $<< 0.05$ were obtained, resulting in a significant catch reduction when using the pulse gear.

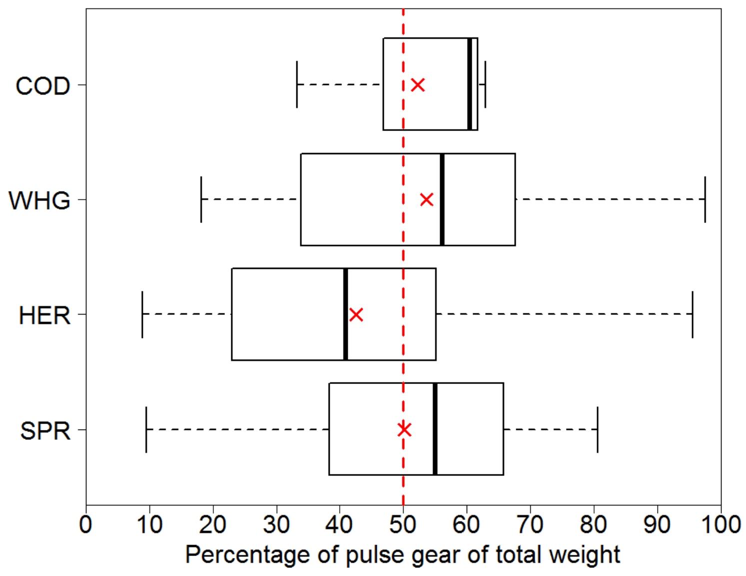
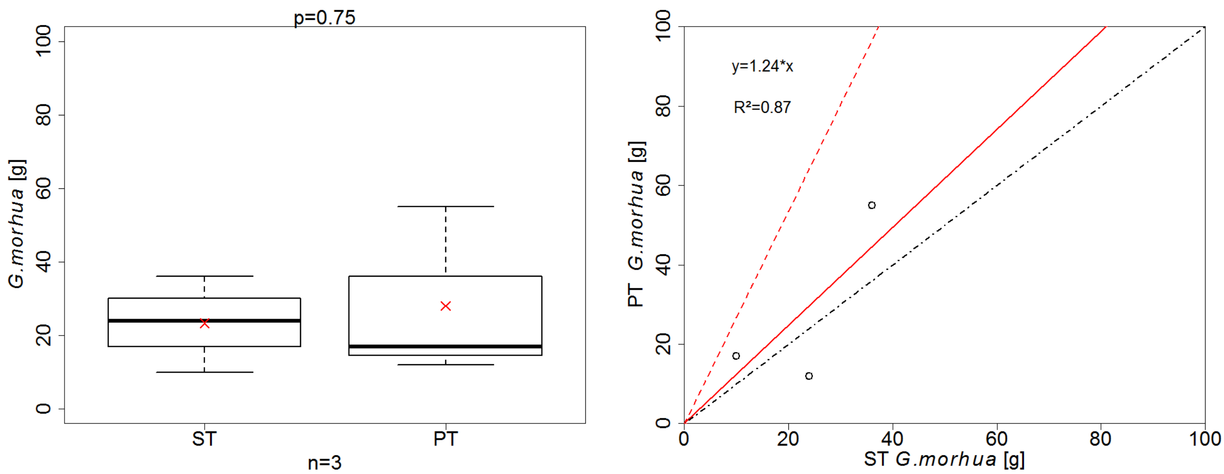


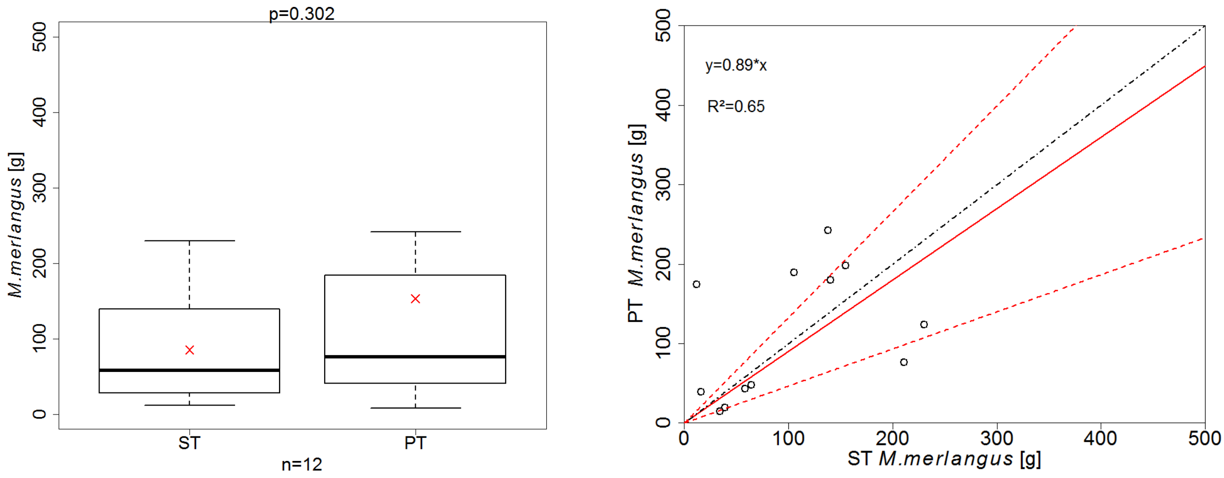

**Figure 61: Comparison of share of pulse trawl in overall weight of commercial roundfish: *G. morhua* (COD), *M. merlangus* (WHG), *C. harengus* (HER), *S. sprattus* (SPR)**

The share of the HOVERCRAN in the weight of all species, except herring, does not indicate any tendency. The share varies around the 50% mark. For herring, most values lie beneath the 50% mark, but there is at least one value exceeding the 60% share of the pulse gear.

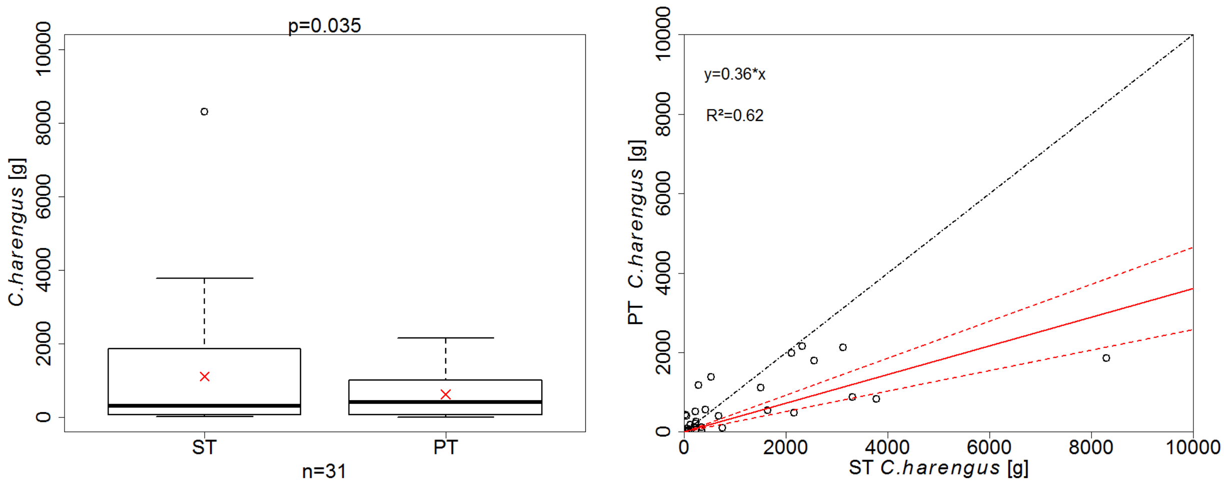
**(A)**



**(B)**




**(C)**




**(D)**

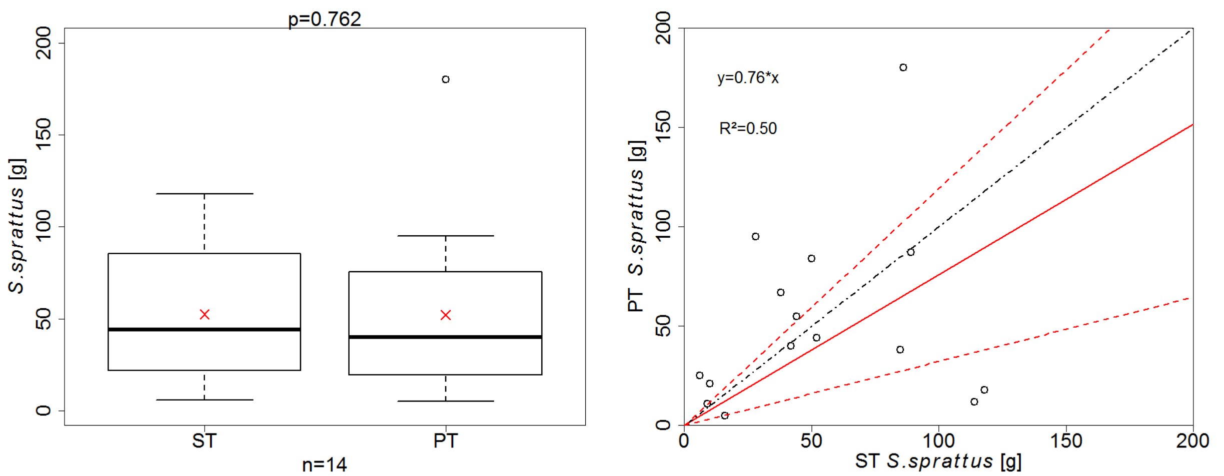



**Figure 62: Comparison of the weights of commercial roundfish according to standard trawl (ST) and pulse trawl (PT). (A) *G. morhua*, (B) *M. merlangus* , (C) *C. harengus*, (D) *S. sprattus*. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples.**

As Figure 61 suggests, there is no significant differences between the gears in catching roundfish. The only exception is herring, where more herring were caught using the standard gear. All p-values calculated with the Wilcoxon Sign Rank Test lie above the threshold of 0.05 and the t-test conducted for the slope of the linear regression also resulted in a non-significant difference from 1. The poor fit for cod (*G. morhua*) is due to the fact, that only 3 data points are available to apply a linear regression to.

b) Length distribution

Table 30 gives an overview of the maximum, minimum and median length ($l_{max}$, $l_{min}$, $l_{med}$) of all measured individuals. The length distribution is shown for the frequently observed flatfish species and the main commercial roundfish species in Figure 63 and Figure 64. Only hauls with the HOVERCRAN switched on are included.

**Table 30: Maximum, minimum and median length of measured individuals sorted by species for standard and pulse trawl in the by-catch fraction**

| | | | Standard trawl | | | | Pulse trawl | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | species | individuals | $l_{min}$ | $l_{med}$ | $l_{max}$ | individuals | $l_{min}$ | $l_{med}$ | $l_{max}$ |
| flatfish | Commercial species | *Limanda limanda* | 72 | 4 | 5 | 6.5 | 43 | 4 | 5 | 6 |
| | | *Microstomus kitt* | 3 | 6 | 6.5 | 7 | 1 | | 7 | |
| | | *Psetta maxima* | 3 | 3.5 | 3.5 | 3.5 | | | | |
| | | *Scophthalmus rhombus* | | | | | 1 | | 9.5 | |
| | | *Pleuronectes platessa* | 229 | 4.5 | 7.5 | 11 | 469 | 5 | 8 | 12 |
| | | *Solea solea* | 268 | 5 | 7.5 | 10 | 188 | 5.5 | 7.5 | 10 |
| | | *Platichthys flesus* | 41 | 6 | 9 | 32.5 | 10 | 8.5 | 9.25 | 13 |
| | | *Gadus morhua* | 17 | 10 | 12 | 16 | 6 | 11 | 12.25 | 13.5 |
| | | *Merlangius merlangus* | 76 | 8.5 | 12.5 | 16.5 | 50 | 9.5 | 13 | 18.5 |
| | | *Clupea harengus* | 298 | 7 | 10 | 13 | 368 | 7.5 | 9.5 | 12.5 |
| | | *Sprattus sprattus* | 76 | 5 | 8.5 | 13 | 56 | 7 | 8.5 | 10.5 |
| | | *Osmerus eperlanus* | 179 | 5 | 13 | 18 | 454 | 6 | 12.5 | 20 |
| | | *Alosa fallax* | 67 | 5.5 | 8 | 16 | 48 | 6 | 8 | 17 |
| | | *Liparis liparis* | 131 | 5 | 6.5 | 8.5 | 73 | 5 | 6.5 | 8 |
| | | *Pomatoschistus minutus* | 120 | 3 | 6.5 | 8 | 56 | 4.5 | 6.5 | 8.5 |
| | | *Ciliata mustela* | 60 | 5.5 | 10.5 | 19 | 31 | 7.5 | 11.5 | 18.5 |
| | | *Pholis gunnellus* | 60 | 10 | 14 | 17.5 | 48 | 5.5 | 14.5 | 16 |
| | | *Ammodytes tobianus* | 16 | 14.5 | 15.75 | 17 | 37 | 13.5 | 16 | 17 |
| | | *Agonus cataphractus* | 42 | 4 | 5 | 11 | 19 | 4 | 5 | 10 |
| | | *Lampetra fluviatilis* | 14 | 17 | 21 | 34 | 30 | 15 | 21 | 34 |
| | | *Myoxocephalus scorpius* | 23 | 5.5 | 7 | 8.5 | 14 | 6.5 | 7.25 | 17 |
| | | *Zoarces viviparus* | 7 | 12 | 17 | 20 | 8 | 12.5 | 16.5 | 20.5 |
| | | *Scomber scombrus* | 9 | 22 | 23.5 | 27 | 5 | 21 | 24.5 | 25 |
| | | *Trachurus trachurus* | | | | | 3 | 6.5 | 7 | 7.5 |
| | | *Callionymus lyra* | 2 | 11.5 | 12.75 | 14 | 2 | 12 | 12.25 | 12.5 |
| | | *Chelidonichthys lucerna* | 2 | 6 | 7.5 | 9 | 3 | 5 | 7 | 8 |
| | | *Belone belone* | 1 | | 11 | | 1 | | 11 | |
| | | *Gasterosteus aculeatus* | 1 | | 2.5 | | | | | |
| | | **Sum** | 1817 | | | | 2024 | | | |

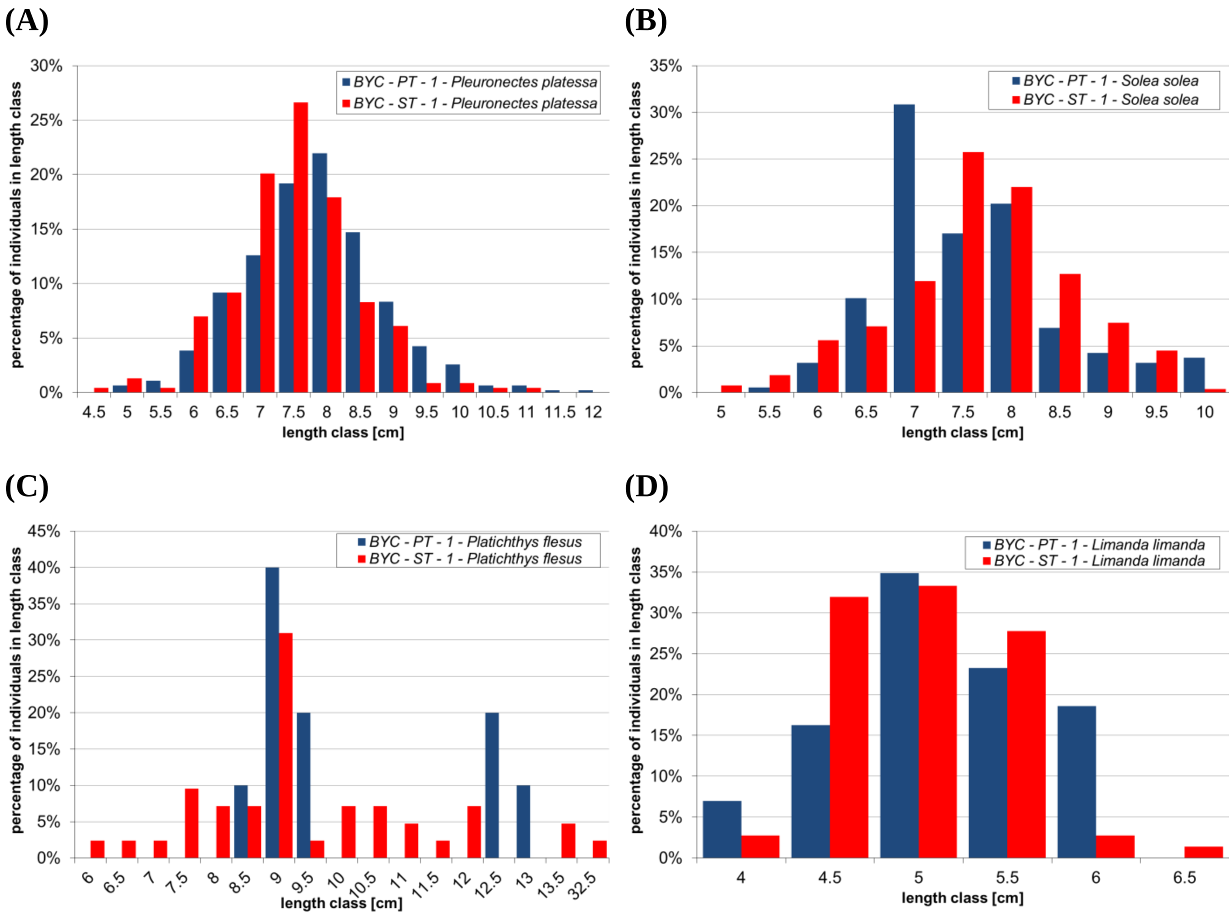



**Figure 63: Length distribution of flatfish with high frequency in the by-catch fraction sorted by standard trawl (ST, red) and pulse trawl (PT, blue). (A) *P. platessa,* (B) *S. solea,* (C) *P. flesus,* (D) *L. limanda***

Most flatfish caught measure less than 10cm in length. The lengths are normally distributed around 7.5cm - 8cm for plaice and sole and around 5cm for dab. Sole shows additionally an outstanding peak at 7cm for the pulse gear. Flounder shows a peak at 9cm for both gears and another peak at 12.5cm for the pulse gear only. The rest of the length classes are represented with less than 10%. The non-normal distribution of lengths of flounder is due to the fact, that very few individuals were caught overall.

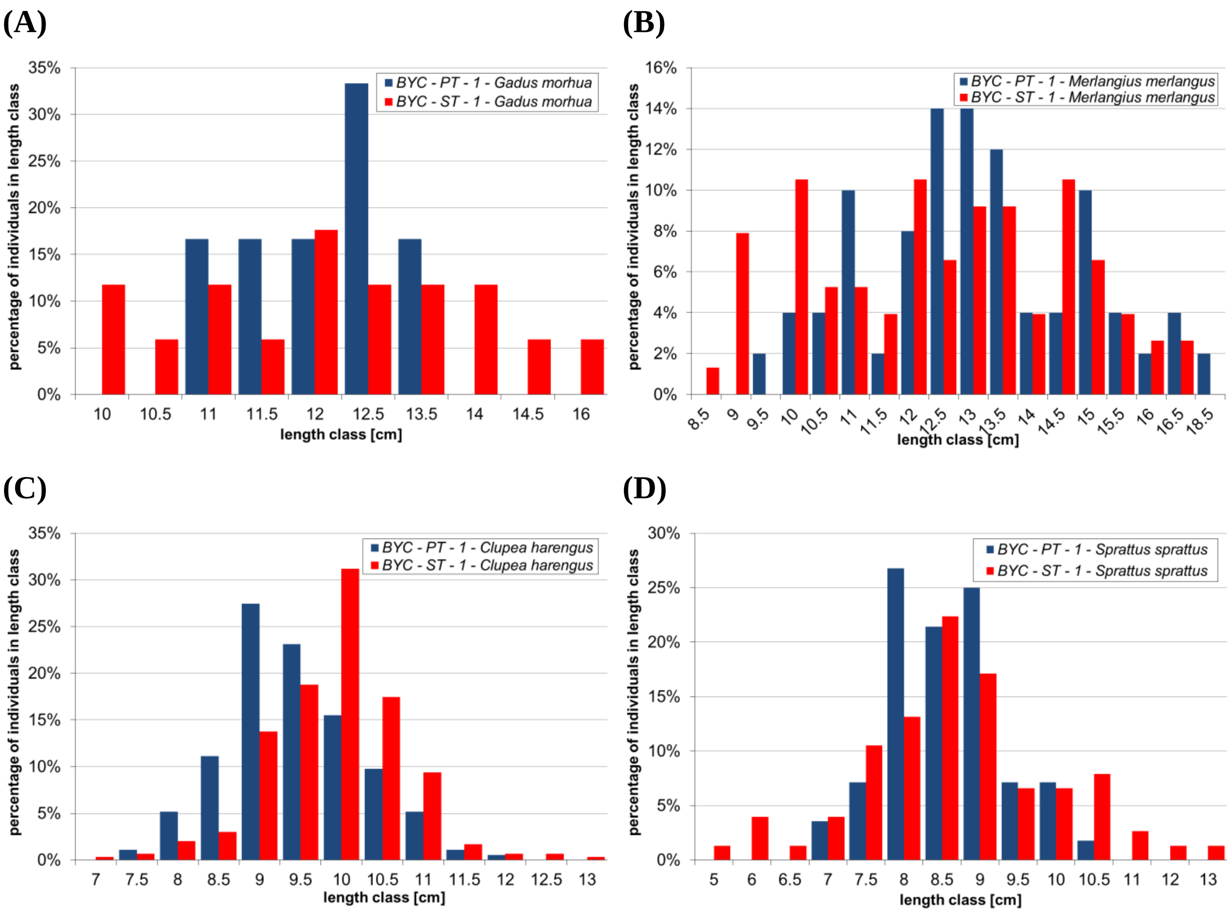



**Figure 64: Length distribution of commercial roundfish in the by-catch fraction fraction sorted by standard trawl (ST, red) and pulse trawl (PT, blue). (A) *G. morhua*, (B) *M. merlangus* , (C) *C. harengus*, (D) *S. sprattus***

Generally speaking, the roundfish caught are larger than the flatfish. Both clupeid species are mainly between 8cm - 10cm long, independent from the gear. For herring, the peak of length is at 9cm for the pulse gear and at 10cm for the standard gear. More than 25% of the measured cod caught with the pulse gear are 12cm long. The standard gear shows almost no peak, the fish are evenly distributed. Most whiting are between 12.5cm - 13cm long in the pulse gear catch, the rest is normally distributed around these values. The standard gear shows peaks of 12% at 10cm, 12cm and 14.5cm for whiting.

Overall, the length distribution is, except for the outstanding peaks in sole and flounder, almost equal for both gears. It has to be kept in mind though, that the number of individuals overall differs greatly.

3.3.3.2 Extra fish

During the first week of the scientific sampling, the shrimp fraction was also sampled for fish by-catch. The analysis of fish in the shrimp fraction is not as detailed as the analysis of the by-catch fraction, since the amount of fish in the sorted shrimps was not noticeably high. Figure 65 shows the percentage of fish in the shrimp section according to the gear. Only hauls with the pulse gear switched on and under conditions of regular salinity were included.

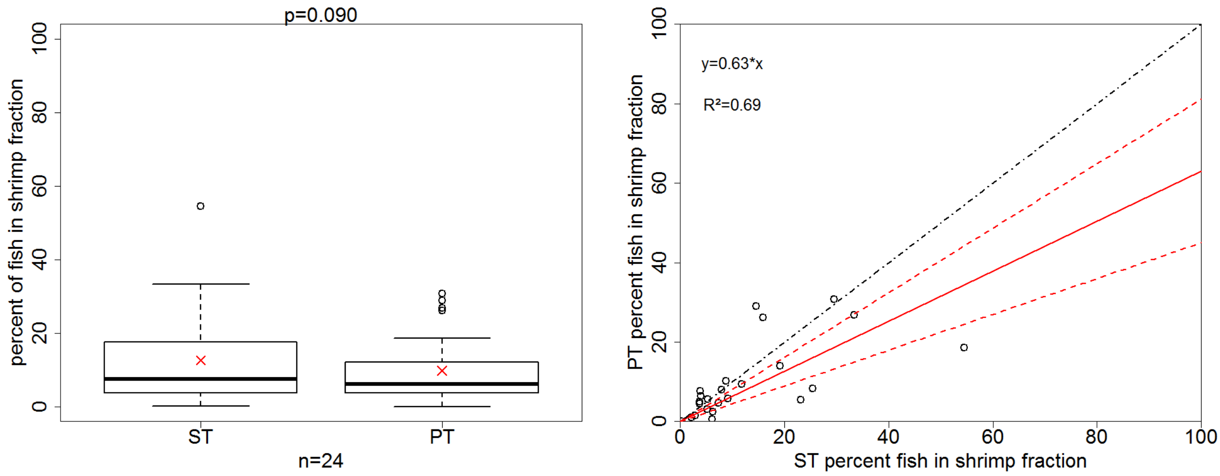



**Figure 65: Percentage of fish in the shrimp fraction for standard trawl (ST) and pulse trawl (PT). The p-value was obtained using the Wilcoxon Sign Rank Test. The means are marked as a red cross. The solid red line is the linear regression with the according confidence intervals (dashed red lines). The identity line is depicted as black dashed-dotted line splitting the plot in half.**

Both, the Wilcoxon Test and the linear regression, show a significant difference between the gears. The lower selectivity of the standard gear also became obvious in the previous chapters (Chapter 3.2.1.2 and 3.3.1.2) and is confirmed through these results. However, it should be noticed, that less than approximately 10% of the shrimp fraction consist of fish. Due to the very low amounts of fish in the individual hauls, a comparison of the weights as done in the previous chapter will not be carried out.

Table 31 gives an overview of the maximum, minimum and median length ($l_{max}$, $l_{min}$, $l_{med}$) of all measured individuals. A length distribution of the most present species (with more than 50 measured individuals) is given in Figure 66. Herring as the only commercially important species present in the hauls is also shown. No flatfish, except one sole and no additional commercial roundfish, except two whitings and four sprats (*S. sprattus*) were observed. Only hauls with the HOVERCRAN switched on were included.

**Table 31: Maximum, minimum and median length of measured individuals sorted by species for standard and pulse trawl in the shrimp fraction**

| | Standard trawl | | | | Pulse trawl | | | |
|---|---|---|---|---|---|---|---|---|
| species | individuals | $l_{min}$ | $l_{med}$ | $l_{max}$ | individuals | $l_{min}$ | $l_{med}$ | $l_{max}$ |
| *Solea solea* | | | | | 1 | | 8.5 | |
| *Merlangius merlangus* | 2 | 8.5 | 8.5 | 8.5 | | | | |
| *Clupea harengus* | 83 | 7.5 | 9 | 10 | 45 | 7.5 | 8.5 | 10 |
| *Sprattus sprattus* | 2 | 7 | 7.5 | 8 | 2 | 8 | 8.25 | 8.5 |
| *Osmerus eperlanus* | 153 | 5 | 10.5 | 13 | 201 | 5 | 10 | 12 |
| *Alosa fallax* | 2 | 7 | 7.5 | 8 | 2 | 7 | 7 | 7 |
| *Liparis liparis* | 15 | 4.5 | 5.75 | 6.5 | 4 | 5.5 | 5.75 | 6 |
| *Pomatoschistus minutus* | 108 | 5 | 6.5 | 8.5 | 68 | 5 | 6.5 | 7.5 |
| *Ciliata mustela* | 6 | 8 | 9.25 | 11 | 3 | 8.5 | 9.5 | 10 |
| *Pholis gunnellus* | 1 | | 15 | | | | | |
| *Ammodytes tobianus* | 1 | | 4 | | 2 | 16 | 16 | 16 |
| *Agonus cataphractus* | 54 | 4 | 4.5 | 5.5 | 39 | 4 | 5 | 6.5 |
| *Lampetra fluviatilis* | 3 | 17 | 19 | 20 | | | | |
| *Myoxocephalus scorpius* | 1 | | 7 | | 1 | | 6 | |
| *Zoarces viviparus* | | | | | 1 | | 13 | |
| *Scomber scombrus* | 2 | 24 | 24.75 | 25.5 | | | | |
| *Trachurus trachurus* | 1 | | 6 | | 2 | 6 | 6 | 6 |
| **Sum** | 434 | | | | 371 | | | |

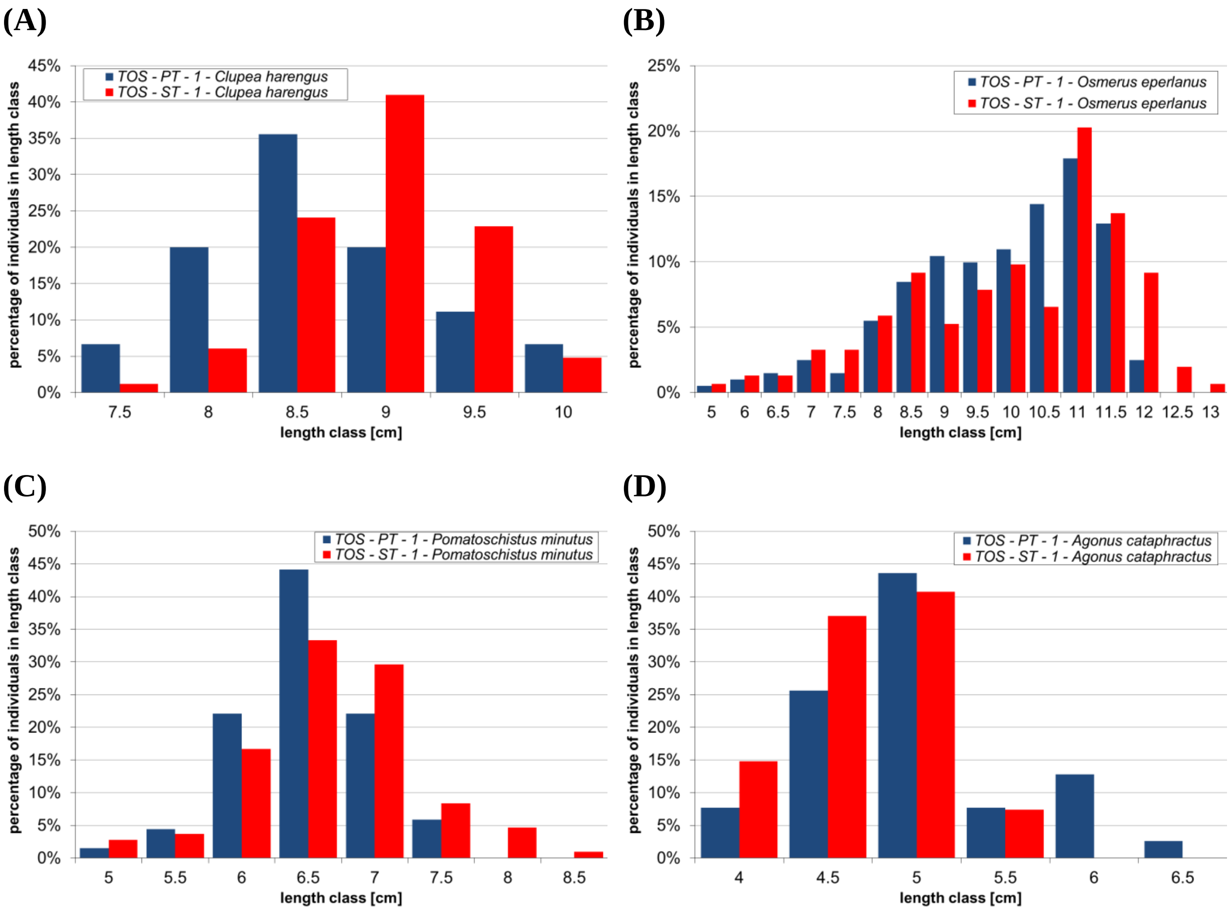



**Figure 66: Length distribution of most species with more than 50 fish measured in the shrimp fraction sorted by standard trawl (ST, red) and pulse trawl (PT, blue). (A) *C. harengus*, (B) *O. eperlanus*, (C) *P. minutus*, (D) *A. cataphractus***

The length distributions of all species follow a normal distribution. The peak in length of herring lies at 8.5cm for the pulse gear and at 9cm for the standard gear. Compared to the lengths observed in the by-catch fraction (Figure 64(C)), the fish in the shrimp fraction are smaller by 1cm. Smelt (*O. eperlanus*) shows a slightly right-shifted peak at around 11cm for both gears. Most sand gobies (*P. minutus*) are between 6cm - 7cm long. The length peak for hooknose (*A. cataphractus*) lies at 5cm, for both standard and pulse gear. Generally speaking, fish sorted into the shrimp fraction have a similar shape and width as marketable *C. crangon* and are also smaller than fish sorted out in the by-catch fraction.

### 3.3.4 Comparison of the calculated total catch and measured total catch

Theoretically, if the volumes of all uncooked fractions are added up, the result should be equal to the measured volume of total catch. This would allow the calculation of missing data, if all fractions but one are present. In this section, the hypothesis stated in Equation 14 will be reviewed.

$$V_{total\ catch\_measured} = V_{shrimp\ fraction} + V_{undersized\ shrimp} + V_{by-catch} \quad \textbf{Equation 14}$$

In order to evaluate the relation between the calculated and the measured total catch, the two values are visualized in Figure 67. A linear model is applied to the data and a Wilcoxon Sign Rank Test is performed evaluating whether or not there is a significant difference between the methods.

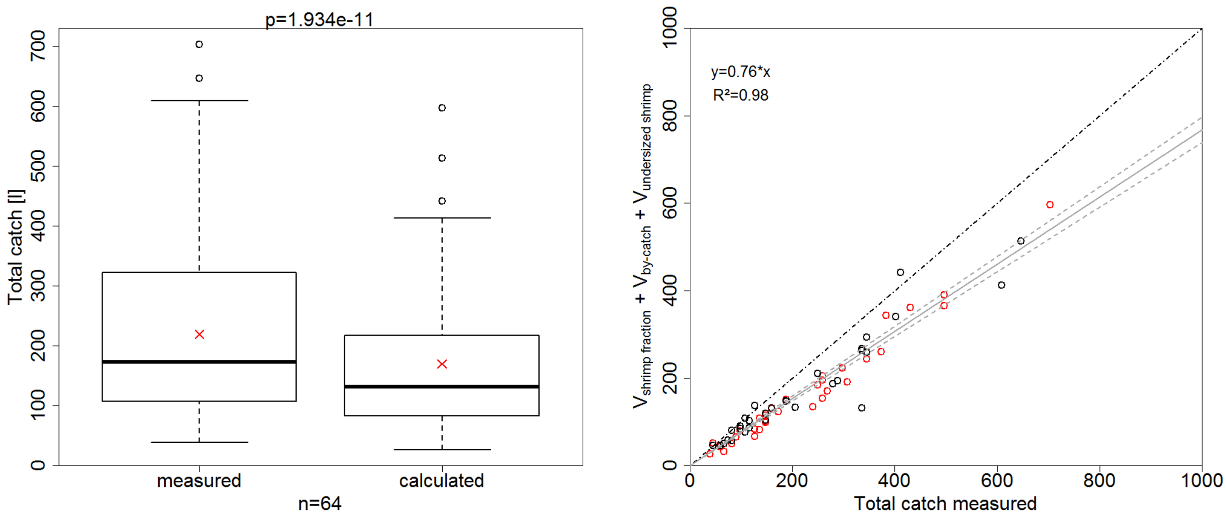



**Figure 67: Comparison of the measured total catch to the calculated total catch. The p-value is calculated using the Wilcoxon Sign Rank Test for paired samples. The colors in the scatterplot indicate the two gears: standard trawl (black) and pulse trawl (red). The linear regression model is applied without distinguishing between the two gears and shown as the grey solid line with the according confidence intervals (dashed grey lines). The identity line is depicted as black dashed-dotted line splitting the plot in half. The means are marked with red crosses.**

Generally speaking, the smaller the total catch, the better the methods correlate. However, the calculated total catch is overall 24% smaller than the measured total catch and the Wilcoxon Test shows a significant difference between the methods. Consequently, the hypothesis in Equation 14 is rejected. It is not possible to calculate a missing fraction using the correlation between measured and calculated total catch. As a result, the calculated undersized shrimp fraction in Figure 20, Figure 28 and Figure 41(A) needs to be handled with care.

## 3.4 Comparison of self-sampling and scientific-sampling

In this chapter, the results of self-sampling and scientific-sampling will be compared. Table 32 shows an overview of the p-values obtained with the Wilcoxon Test as well as the slope of the linear regression. The significance difference is achieved when the p-value lies below the threshold of 0.05. A slope significantly greater than 1 shows a trend of a higher volume caught in the pulse trawl, whereas a slope smaller than 1 shows, that a higher volume of the respective fraction is caused using the standard trawl.

**Table 32: Comparison of self-sampling and scientific-sampling regarding the p-values and the slope of the linear regression. Significant differences are marked with an asterisk.**

| | Wilcoxon Test | | Linear regression | |
|---|---|---|---|---|
| | Self-sampling | Scientific sampling | Self-sampling | Scientific sampling |
| Total catch (TOT) | 6.57e-14* | 0.247 | 1.17* | 0.99 |
| Shrimp fraction (TOS) | 3.44e-08* | 0.365 | 1.11* | 0.98 |
| By-catch (BYC) | 1.5e-09* | 1.272e-05* | 0.85* | 0.67* |
| TOS : TOT | 6.79e-11* | 0.180 | 0.84* | 0.93 |
| BYC : TOT | <2.2e-16* | 3.492e-10* | 0.59* | 0.61* |
| (TOS+BYC) : TOT | 3.79e-15* | 0.011* | 0.81* | 0.87* |
| BYC : TOS | <2.2e-16* | 2.006e-06* | 0.69* | 0.66* |
| CPUE TOT | 7.34e-10* | 0.175 | 1.19* | 1.04 |
| CPUE TOS | 3.84e-05* | 0.256 | 1.11* | 1.05 |
| CPUE BYC | 1.14e-09* | 7.236e-05* | 0.86* | 0.66* |

A significant difference in by-catch could be observed during both sampling phases. This applies to the absolute volume, the CPUE, as well as the ratios of by-catch to shrimp fraction and by-catch to total catch. Interestingly, there is no difference in the shrimp fraction and the total catch during the scientific-sampling. In both of the sampling phases, the shrimp fraction and the by-catch fraction make up the larger part of the total catch when using the standard gear, thus a third fraction, possibly the undersized shrimp, should be larger when fishing with the pulse gear.

# 4 Discussion

In this thesis, the performance of a *Crangon*-pulse trawl system was compared to the performance of the traditional gear used in the German *Crangon* fishery. The installation of a HOVERCRAN with a modified bobbin rope on starboard of the commercial *Crangon* vessel SD33 “Marlies” while on portside the traditional gear was left in use, allowed a direct catch comparison of the two gears. The data were mainly gathered via self-sampling by the crew of the vessel. The self-sampling was monitored by regular attendance by a scientist during the trips. Ten days of intensive sampling by scientists was included.

The two main hypotheses in this study were:

1. The electric field between the electrodes substitutes the bobbins as a stimulus for startling shrimp and thus there is no loss in shrimp catches.
2. The reduced number of bobbins in the modified bobbin rope opens an escape route for unwanted fish and thus less by-catch is produced using the pulse gear.

## 4.1 General analysis

For both sampling phases both hypotheses can be accepted, as the pulse gear performed equally well or slightly better. Under strictly commercial conditions during the self-sampling phase, a significant difference between standard and pulse gear was found in all fractions. The pulse gear caught 10% more shrimp than the standard gear while reducing by-catch by 15% at the same time. Simultaneously to these changes in shrimp and by-catch, the total catch volume was higher when using the pulse gear. Higher shrimp catches and lower by-catch rates when using the HOVERCRAN-system have also been found in the studies by the Belgian institute ILVO (ICES WKPULSE, 2010). In those trials, lower total catch volumes were achieved with the pulse gear. The higher shrimp catches in the present study may be caused by two factors:

- The bobbins on the modified bobbin rope act as an additional stimulus to the electric field and thus more shrimp are caught. A strong correlation between pulse stimulus and remaining bobbins resulting in higher catches was also found on Dutch vessels (ICES SGELECTRA, 2012). The vessel with the configuration of 9 bobbins and 12 electrodes showed a 10% catch increase, corresponding to the results in the present study.

- The standard gear uses an unspecific mechanical stimulus to startle shrimp. The bobbin rope creates water turbulence and vibrations which stimulate the shrimp (BERGHAHN *et al.*, 1995). In contrast to this unspecific stimulus, the HOVERCRAN-pulse is a *Crangon*-specific pulse as the frequency of 4.5Hz corresponds to the tail-flip movement of *Crangon crangon* (VERSCHUEREN, personal communication, 2012). As a result, the highly specified stimulus may result in more startled shrimp and thus higher catches.

During the self-sampling phase, the median share of the shrimp fraction (excluding undersized shrimp sorted out in the rotating sieve) in the total catch was 40% for the pulse gear and 44% for the standard gear; the by-catch median lay at 4% for the pulse gear and 6% for the standard gear. A maximum of 20% by-catch was recorded for the pulse gear. Similar results for the standard gear, though with higher by-catch rates and less data were found by ULLEWEIT *et al.* (2008, 2010). Dutch scientists also reported similar results (ICES WGCRAN, 2010). The study by AVIAT *et al.* (2011) points out that there is a highly seasonal variability with lower by-catch rates during the summer months, i.e. July and August. The here represented data covers exactly this time of the year.

Similar results were found during the intensive scientific-sampling at the end of August 2012. Even though there was no significant difference regarding the shrimp and total volume, there was a significant by-catch reduction by 33% compared to the standard gear. The crucial point is that the implementation of the pulse gear did not lead to a reduction in shrimp catches, which was found for some cases in POLET *et al.* (2005b), but to a reduction in by-catch. The median share of by-catch in the total catch is 2.5% for the pulse gear and 6.8% for the standard gear, whereas the commercial sized shrimp made up close to 40% of the total catch on both sides.

The self-sampling data also revealed that the calculated undersized shrimp fraction had a higher share in the total catch when fishing with the standard gear. This resulted from a subtraction of the by-catch and the commercial shrimp from the total catch, in relation to the total catch.

Since the pulse is a *Crangon*-specific pulse, it would affect both juvenile and adult shrimp and thus enlarging the fraction of undersized shrimp when fishing with the pulse gear. In POLET *et al.* (2005a) it was stated that an electric field of 24V/m (the strength of the present electric field is approximately 30V/m) is sufficient to startle shrimp in every length class independent of their position in relation the electric field. It is not specified whether the shrimp referred to as “small” shrimp are undersized or market sized.

Despite the assumption that the undersized shrimp must be responsible for making up the remaining volume of the total catch – 40% are commercial shrimp and approximately 5% are by-catch – there is no significant difference between standard and pulse gear when the measured undersized shrimp fraction is considered.

Since the entire catch is sorted automatically and all fractions – except undersized shrimp during the self-sampling – are collected in baskets, it is highly unlikely that another fraction is responsible for the remaining volume. It is rather probable, that the discrepancy between the measured total catch and the sum of the three fractions plays an important role in these contradictory results. When calculating the ratios and thus the percentages of each fraction in the total catch, the absolute volumes are considered. Since there is a 25% difference between the measured total catch and the sum of the fractions, the calculated ratios involving the measured total catch volume need to be handled with care. The difference between measured and calculated total catch is caused by a variety of possible reasons.

- Due to the mixture of shrimp, fish and debris, more space between the individuals is created than, e.g. in a basket with all flatfish, where the organisms are more condensed. This may lead to an additional volume of air in the hopper that is not present anymore once the catch has been sorted. The space between the individuals could also be filled with water. When the haul is completed a fair amount of water is also drawn up with the net and added to the hopper. Once the catch runs through the sorting, there is less water in the fractions.
- The “human factor” is of major importance where the difference between the calculated and measured total catch is concerned. Firstly, the total catch volume is not determined in the same way as the volumes of the other fractions. Whereas all sorted fractions are all measured with identical baskets, the total volume is calculated based on a model that derived from a complex volumetric measurement. Assuming that minor errors made in this measurement are evened out by the application of a best fit curve, the measurement of the height of catch in the hopper is largely dependent on the person measuring. Before measuring the height of the catch (which is used to calculate the volume), the surface of the catch is evened out by eye, but small aggregations of shrimp and fish leading to an unleveled surface cannot be ruled out.

Keeping in mind that 1cm in height roughly corresponds to 10L of catch, even small errors during leveling lead to a large error. In addition to that, the baskets used for the measurement of the sorted fraction volumes are only marked in intervals of 5 liters for the sake of usability and were subject to volumetric measurement as well. Consequently, a measurement error could be caused by the volumetric measurement itself, as well as the estimation of values between multiples of five. In summary, it can be stated that the accuracy of the measurements highly depends on the thoroughness of the person in charge.

All of these factors influence the quality of the measurements leading to problems in the analysis of the results. The errors are insofar of minor relevance as they apply to both gears in the same way, and thus the comparison of the two sides is still valid. Difficulties arise when conclusions about one fraction have to be drawn based on the evaluation of another fraction. During the self-sampling phase, the assumption that undersized shrimp make up a larger volume in the HOVERCRAN catch was based on the calculation of the undersized shrimp fraction by subtracting the by-catch and the commercial shrimp fraction from the total catch. Since the absolute volumes of all fractions need to be handled with care, such reasoning is difficult to support. The issue of the undersized shrimp fraction needs to be investigated further. In addition to the potentially faulty absolute measurements, it has to be kept in mind that the amount of data sets collected via the self-sampling is almost four times higher than the data sets collected during the first scientific-sampling phase. It also has to be noted that the towing duration during the scientific-sampling phase was much shorter than during the self-sampling phase, thus less data were collected. This may lead to weaker signals in differences between both gears.

Even if it is assumed, that the real total catch volume is 25% smaller than assumed and thus the by-catch rates are 25% higher, this still leads to by-catch rates lower than 10% of the total catch. Nevertheless, it must be kept in mind that due to the very small fish in the by-catch fractions the number of individuals in a certain volume is higher than in many other trawl fisheries.

### 4.1.1 Effect of parameters on the catch

The catch composition and catch volumes depend on a variety of factors (AVIAT *et al.*, 2011). In this study, no significant differences in shrimp catches between high and low salinity levels could be found. According to SIEGEL *et al.* (2005) the distribution of

*Crangon crangon* is within the salinity limits of 27 – 35 in the German Bight. Since the hauls carried out in the Elbe estuary shows a salinity of 16, fewer shrimp were present in general. As a smaller population was available to be fished, lower catches and thus weaker signals result in the significance tests. The by-catch rates in this area were equal on both sides; the reason for this is currently unknown. It must be kept in mind though, that the statistical analysis of these hauls is difficult to evaluate. The very number of hauls conducted at low salinity is very low compared to the hauls conducted during conditions of regular salinity. Ten times more hauls were conducted at a salinity of 27 than at a salinity of 16. Further research is necessary to increase the certainty and assess the reliability of these results.

As many other shrimp species, *Crangon crangon* is nocturnal (HAGERMAN, 1970). They are buried during the day and feed on the sea floor during twilight. Higher catches have been observed by the fishermen during conditions of low light. The activity pattern of *Crangon crangon* might have an influence on the catchability (ADDISON *et al.*, 2003).

The hauls conducted during the self-sampling phase were analyzed for all fractions and categorized for the time of day: day, twilight and night. All fractions, except the by-catch, showed no significant difference at night. This means, that either the pulse gear shows a lower catch rate at night or the standard gear has higher catches during the night, which results in an equal amount of catch fractions compared. Interestingly, the signal difference is only visible when the night hauls are compared directly in a paired sample test, which makes it difficult to determine whether the pulse gear performs worse or the standard gear performs better; it may also be a combination of both effects. The unpaired tests comparing the performance of the gears among themselves for the three intervals resulted in no significant difference. Theoretically, as one of the gears is showing a different kind of behavior, there should be a difference between day and night when only one gear is considered. A reason for this lack in difference could lie in the nature of the Wilcoxon Test. When unpaired samples are compared, the differences have to be very high for a statistically significant signal to become obvious. Since many more hauls were conducted during the day than under low light conditions it is difficult to compare the two data sets and receive a convincing result. Furthermore the variance within the data sets is higher than in the comparison of the data sets. Most fishermen conduct fishing trips overnight. Therefore, the evaluation of the gear performance during the night is of major importance and it is necessary to conduct further hauls at night to receive a clear result.

Higher by-catches during the night can be explained by the nocturnal activity of flatfish (GIBSON, 1997). As they often rise into the water column, they may not be able to use the escape route underneath the net and are therefore caught. The operation of the HOVERCRAN without pulses proves that the fish are using the provided space between the bobbins to escape. If another factor, associated with the pulse gear, would trigger the escapement there would significant difference between the HOVERCRAN with and without pulses. When the pulses were switched off, the HOVERCRAN showed a slightly, but not significant, lower share in the overall by-catch compared to when the pulses were running. This can be due to the fact that a weaker signal is evaluated as fewer hauls were conducted without pulses. Sensitive species, like *S. solea* and *L. limanda* ,showed active responses when they sensed the electric field (POLET *et al.*, 2005a; VERCAUTEREN *et al.*, 2010). It might be possible that even less by-catch was produced when the HOVERCRAN was switched off, as these animals were not affected during those hauls.

Another potentially important factor is the speed of the vessel. Sole-fishery is using reduced speeds when fishing with a pulse gear (VAN MARLEN *et al.*, 2011; STEPPUTTIS, personal communication, 2012). A side effect of this is that direct comparison of standard and pulse gears, as done in this study, is not possible. Hauls at different speeds were conducted during the intensive scientific-sampling phase and catches were compared.

No significant difference between the gears at different speeds was found for all fractions, except the by-catch. There was also no significant difference when the gears themselves were compared at different speeds. Where the by-catch rate is considered, there was a significant difference between the gears when the vessel tows at the regular speed of 3kn. Lower and higher speeds resulted in an equal share in the overall by-catch by the two gears when the Wilcoxon Test is applied. On the other hand, the linear regression showed that there is a significant difference and thus the by-catch is higher on the standard gear side. The discrepancy in this case is attributed to the nature of the Wilcoxon Test and needs to be investigated further. It must also be kept in mind, that the number of hauls at regular speed is higher than at lower and higher speeds.

### 4.1.2 By-catch composition

The by-catch fraction sorted out by the rotary sieve consists mainly of flatfish, with plaice (*P. platessa*) as the most abundant species. Herring (*C. harengus*) was the most abundant commercial roundfish species and smelt (*O. eperlanus*) the most abundant roundfish overall.

Abundance is related to individual fish. The frequency of all species is roughly equal. The only noticeable difference in frequency is visible for flounder (*P. flesus*), however, the same number of individuals is caught. The overall by-catch reduction is mainly caused by less flatfish. The reduction in weight when using the pulse trawl is 40% for plaice, 45% for sole, 24% for flounder and 70% less dab (*L. limanda*). It has to be kept in mind though, that the reduction in weight does not always correspond to the reduction in individuals. Since most fish caught are juvenile, the number of fish is of greater relevance than the actual weight, as it is possible to catch a low weight but a high number of small fish (BERGHAHN & PURPS, 1998). The reduction in individuals showed 30% fewer plaice and 50% fewer dab in the HOVERCRAN-catches compared to the standard trawl. The number of flounder was nearly the same, the weight reduction can be ascribed to the lower weight of the smaller individuals caught by the pulse gear. One individual in the standard gear catch was 32.5cm and many above 10cm. Most flounder caught using the HOVERCRAN were 9.5cm or smaller and thus lighter. Similar results were achieved in Belgian trials (ICES WKPULSE, 2010).

Most commercial roundfish showed a 50-50-share of the standard and pulse gear considering the weight. The only roundfish showing a significant difference between the gears was herring. A 70% catch reduction was achieved with the pulse gear. The catch reduction for this pelagic species is not present when the pulse is off. Since the alteration of the bobbin rope is the device for by-catch reduction and thus primarily species selective for flatfish, an explanation of the catch reduction of herring is needed. During a few hauls large numbers of herring were caught using the standard gear in comparison to the pulse gear. The most likely explanation is that an entire school of herring was caught – possibly by accident – in the standard trawl in those cases, as most other hauls showed the same number of individuals in both gears. It is possible that these single events highly contribute to the catch reduction. The removal of these events still results in a 25% catch reduction of herring using the HOVERCRAN. DOMENICI & BATTY (1997) reported longer latencies of schooling herring compared to individuals in flight reaction to a sound stimulus. In contrast to this result, WEBB (1980) reported shorter latencies of schooling fish than individual fish when an electric stimulus was applied. As the catch reduction is not present when the pulse is turned off, a relationship between reduced amounts of herring and the electric field is possible. Generally speaking, the reduction of roundfish using the HOVERCRAN is difficult even with the altered bobbin rope. The created escape route is mainly suitable for flatfish species. When comparing by-catch rates of the standard trawl and the pulse trawl it is important to distinguish between the species. Considerations of the by-catch reduction mainly apply to flatfish.

Assuming a normal distribution of length classes, as a sub-sample was taken from the by-catch, the majority of fish present in the by-catch fraction vary between 5cm – 11cm in size; few individuals are larger 20cm. As all hauls were conducted with a sieve net inserted in the net on both sides, this is an indicator that this sorting device serves its purpose. POLET *et al.* (2004) as well as REVILL & HOLST (2004) reported that the sieve nets currently mandatory by Council Regulation (EC) No. 850/98 during the fall and winter, have good selective properties for fish larger than 10cm.

The analyzed length distributions show hardly any difference between pulse and standard gear. The distribution of sole showed a peak of 30% of all measured individuals at 7cm for the pulse gear that is incoherent with the rest of the distribution. A stronger response of sole to the pulse-trawl for some length classes was also reported in VERSCHUEREN (2010), but the relevant length classes here are 20cm and above and none such individual was found in the current study. In general, VERSCHUEREN (2010) has found larger individuals compared to this study. However, a size specific response of small sole is possible and should be subject to further investigation.

The selectivity of rotary sieve on board is also satisfying for separating fish. Most hauls during the intensive scientific-sampling showed less than 10% of fish in the shrimp fraction. The reduction is particularly important in this fraction as the by-catch highly fluctuates according to the season (NEUDECKER & DAMM, 2010). Even though no flatfish with the exception of a single sole was recorded, a general fish-by-catch reduction by 37% in the shrimp fraction was noticeable. No commercial species except herring was found in noteworthy amounts. The specimens of herring found in the shrimp fraction were approximately 1cm smaller than in the by-catch fraction. The most abundant species in the shrimp fraction were smelt and sand goby (*P. minutus*). These species are shaped similarly to *Crangon crangon* and it is thus not surprising that they are sorted with the shrimp. The fact, that these fish are cooked with the shrimp and have thus no chance to survive, raises the importance of the issue. One method of reducing by-catch in the shrimp fraction would be improving the selectivity of the rotary sieve, as this is the key element in the fish selection process. An increased space between the bars of the rotary sieve would reduce the number of fish sorted with the commercial shrimp. Simultaneously, this would potentially result in an unwanted loss of market sized shrimp. On the other hand, the data suggest that a fraction of the cooked shrimp are sorted out and discarded as C-shrimp. This fraction, which is thus also unwanted by-catch, becomes obvious when the volume of landed shrimp (A-shrimp + B-shrimp) is compared to the volume of the shrimp fraction prior to cooking. The median value of the ratio is 0.67 for the standard gear and 0.69 for the pulse gear. Thus a loss of volume of 30% is shown. Thereof, approximately 10% of the shrimp fraction volume can be attributed to fish and there could be a minor volume loss during cooking. As a result, 20% of the sorted shrimp fraction will not actually be utilized as a product, but will be discarded as dead animals. Similar results for cooked shrimp to shrimp fraction ratios were found in LANCASTER & FRIED (2002) where 20% of the commercial fraction was undersized shrimp that were cooked and thus removed from the population.

The presence of C-shrimp in the cooked shrimp fraction implies that there is some potential to increase the bar distance in the rotary sieve without losing commercial shrimp. It would not be necessarily marked sized shrimp that are sorted out, but may be individuals that are unwanted by-catch anyways. The choice of rotary and shaking sieve is up to the fisherman. Discussions with local fishermen revealed that there are large differences between the individual vessels. Therefore, the results obtained in this study are valid for SD33 “Marlies” and vessels with similar sieve configurations.

### 4.1.3 Further observations and prospects

A number of parameters that might cause a change in the catchability of shrimp have been studied in this thesis. Especially the differences between day and night were found. During the self-sampling and the scientific-sampling phase, it has been observed that the gears behave in a similar way at low light levels during the day.

In addition to the time of day, the light level on the sea floor also changes with other factors, such as turbidity of the water. Higher shrimp catches are to be expected when the water is unclear (BOONSTRA & DE GROOT, 1974), leading to higher catches with the standard gear and possibly equalizing the share in shrimp by the standard and the pulse gear. The question whether turbidity causes a non-significant difference between the HOVERCRAN and the standard gear will be evaluated in the future with a turbidity logger installed on the beam.

Due to the reduced number of bobbins the pulse gear should be lighter than the standard gear. The actual drag force of the two gears will be measured during scientific-sampling at the end of October. The weight reduction has advantages as well as disadvantages. The observed advantage is the reduced fuel consumption as the engine has to overcome less friction. Also, the sea bed is possibly less disturbed. On the other hand, the pulse gear has shown two major drawbacks:

1. The autopilot of the vessel could not compensate the lacking drag on starboard and thus the rudder often had to be controlled manually to avoid drift. This drawback is limited to the project phase as two different gears are towed by the same vessel. Once the same gear is installed on both sides of the vessel, the drag force is equal and no further difficulties should arise.
2. Losses in shrimp catch were observed by the fisherman during heavy swell. It is assumed that the lighter gear lifted off the bottom and thus caught less shrimp.

The second issue is more complicated to handle. The addition of weight to the gear by adding weight to the trawl head counteracts the positive fact of less disturbance of the sea bed. VORBERG (1997) showed in a thorough study that the bobbin rope and especially the trawl head disturb the sea bed. Even though no ecological consequences were assumed, there was a direct effect on the benthic community. On the other hand it must be kept in mind that the Wadden Sea is a system with a high turnover (PETERSEN & POTT, 2005) and thus the organisms are prone to change. Another solution could be the reduction of speed when two pulse gears are installed. According to the fisherman, the pulse gear lifted off of the bottom when fishing against the tide.

There is also room for improvement in the by-catch reduction. Despite the scepsis of the fishermen, a trial without bobbins is recommended, as this may lead to further reduction in by-catches. Especially the reduction of demersal roundfish could be improved as a larger escape route would be available. DESENDER (2012) presented the latest results of Belgian trials with a 32% reduction in whiting. Further investigations on other species and different life stages of fish were also conducted in Belgium (DESENDER, 2012; DESENDER *et al.*, 2012). The selectivity of the pulse gear and the standard gear could be also be improved by adding a Nordmøre grid in front of the codend. The good selectivity of this device has been subject to testing with good results in GRAHAM (2003).

The effect of by-catch reduction on the population dynamics of the caught species was not investigated during this study. Nevertheless, it is assumed that it has a positive effect on the recruitment of all species, especially plaice, as the number of caught juveniles was majorly lowered. A by-catch reduction automatically leads to a lower mortality overall, as the fish are not caught at all. However, since the implementation of effective rotary sieves the survival rates of flatfish are relatively high (NEUDECKER & DAMM, 2010).

The introduction of pulse fishing in European waters could lead to moderate catch increases of 10%. Even though, this slight catch increase is not assumed to have a strong impact on the population, further investigation of the potential effects on the *Crangon crangon* population is necessary before introducing pulse fishery.

This is especially important, since the shrimp in European waters only has few regulations and no quota (INNES & PASCOE, 2007). As the introduction of pulse fishing in shrimp fishery has led to overfishing in the past (YU *et al.*, 2007), a discussion on how to prevent such an event in the European Union should be carried out. Possible ways of avoiding exploitation of the population could be the introduction of a quota or a seasonal ban in certain areas.

Aside from a general discussion, it is necessary to specify the characteristics of the pulse gear in use. The HOVERCRAN-system with the modified bobbin rope suggested in this thesis could create a moderate catch increase and a reduction of by-catch. As a misuse of the originally proposed gear in China led to problems, there should be limits set to the pulse characteristics.

A definite maximum needs to be set on voltage, current intensity, frequency and duration of the pulses and power output of the pulse generator. The negative effect of pulse fishing in China was mainly owed to the fact that the currents and voltage were set too high and thus startled too many undersized shrimp. The suggested HOVERCRAN-pulse has shown no negative effect on by-catch species (POLET *et al*, 2005a). However, if the gear is misused it cannot be ruled out that it affects other species. In order to prevent spinal injuries as reported in the sole pulse fishery (VAN MARLEN *et al.*, 2011) and in experiments by DE HAAN *et al.* (2011) a limit must be set to the voltage/meter. The positive characteristics of the shrimp pulse gear could also be applied to the sole pulse fishery. It is currently evaluated to what extend it is possible to apply low frequency and low voltage pulses in the sole fishery (ICES SGELECTRA, 2012).

At the moment the installation of a HOVERCRAN on a vessel costs approximately 70,000€ (ICES SGELECTRA, 2012) without nets or a modified bobbin rope. However, if the regulations by the European Union allow pulse fishing and more pulse gears appear on the market, this price may decrease and due to fuel savings and slightly higher catches the investment could pay off within a reasonable time frame.

Potential improvements of the gear lie in the modified bobbin rope. The materials used in the current bobbin rope are not ideal. Further improvement, especially in the attachment between the bobbin rope and the electrodes, needs to be done. A way to improve the rope would be the usage of material more resistant to wear than the currently used hard rubber. A trial with the addition of a metal ring in order to prevent that the attachments wear off is planned. The core of the bobbin rope could be replaced by, e.g., a special Dyneema® thread that is highly resistant to buckling. Yet, the cost-benefit ratio has to be kept in mind when improvement measures are implemented.

With further research and improvement of the gear, the HOVERCRAN with the modified bobbin rope can be a possible contribution to a more sustainable *Crangon*-fishery.

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## Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit mit dem Thema:

**„Pulse beam trawling vs. traditional beam trawling in German shrimp fishery: a comparative study“**

selbstständig verfasst und keine anderen Hilfsmittel als die angegebenen benutzt habe. Die Stellen an denen andere Werke dem Wortlaut oder dem Sinn nach entnommen sind, habe ich in jedem einzelnen Fall durch Angabe der Quelle kenntlich gemacht.

Rostock, 22. Oktober 2012 Isabella Kratzer