



Reconstructing the past: design and function of Granton otter trawl gear at the turn of the twentieth century, as used in South Africa's first trawl surveys (1897–1904)

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Abstract

Long-term change in marine environments is frequently investigated by comparison of historical and contemporary trawl catches. Such investigations are challenged by unquantified biases due to advances in gear technology and a lack of knowledge on the fishing power of historical trawl designs. To address this problem, historical surveys can be repeated by imitating historical trawl gear and methods. With that goal in mind, we investigated the trawl gear used in 1897–1904 surveys by South Africa's first research vessel, the SS Pieter Faure. Trawl gear materials and dimensions were captured from historical reports, literature and photographs, providing a detailed plan for reconstruction of a trawl net with replicated functionality. The gear consisted of an early 'Granton' otter trawl net made of tarred Manila hemp. The otter doors were flat wooden boards in a steel frame, connected directly to the net headline and ground-rope. The towing speed was estimated to be $1.35 \text{ m}\cdot\text{s}^{-1}$ (2.62 knots). The development of this otter trawling equipment and its fishing performance relative to earlier, later and modern technology is discussed. The results provide a case study of trawling technology used during the first two decades of commercial and scientific otter trawling in South Africa and the UK, and other regions, such as Europe, USA and Australia. This example provides an internationally relevant foundation for studies of historical trawl records, their associated technology and fishing power from the late 19th and early twentieth century.

Keywords Otter trawl gear · Granton · Historical fishery surveys · Fishing technology

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Introduction

Across the globe, ship-based research trawl surveys are a common method to monitor fish stocks and their ecosystems (Jennings et al. 2001). In some countries, they began as early as the late 1800s (Fulton 1895; Department of Agriculture 1898; Holt 1898). A series of trawl surveys conducted by the SS Pieter Faure, in 1897–1904, marked the beginning of systematic research trawl surveys in South Africa. These initial surveys are of considerable importance as they pre-date extensive commercial trawling in the same areas (Lees 1969; Currie 2017), providing rare insight into baseline demersal communities and the subsequent anthropogenic 'footprint' in the region.

Contrasting trawl catches over different periods can contribute valuable knowledge of long-term ecosystem change and anthropogenic impacts on marine animal populations (e.g. Greenstreet and Hall 1996; Greenstreet et al. 1999; McHugh et al. 2011; Heath and Speirs 2012). Yet comparing

trawl catches over time or between different trawl surveys is fraught with unquantified biases caused by differences in the trawl equipment used and methods employed (Rogers and Ellis 2000), as these affect the volume, species and size composition of the catch (Hickling 1931; Margetts 1949; Parrish 1949; Bagenal 1958; Engås and Godø 1986; Engås and West 1987; Dealteris et al. 1989; Axelsen and Johnsen 2015). Therefore, consideration of the trawl gear used and how it may have influenced fishing power is crucial to informative comparisons of trawl catches among different periods or surveys. Modern trawl surveys are typically accompanied by extensive lists of the apparatus employed, their dimensions, configuration and methods used. Such meticulous gear lists are frequently not available for historical survey records, as was the case with South Africa's earliest trawl surveys.

Various components of the trawl design influence the fishing power and selectivity of the net. For example, the mesh sizes and twine material influence the potential escape of organisms as a function of their size and shape (Clark 1960; Sparre and Venema 1998). It is the codend meshes of a trawl net where the greatest selectivity is believed to act (Jensen 1949; Graham et al. 2009). The selectivity factors of a specific mesh can be estimated, usually by way of a covered codend experiment (MacLennan 1992; Sparre and Venema 1998). The shape of the mouth of the net, and the degree of contact between the ground-rope and the sea floor, will influence its selectivity for size and fish behaviour (Engås and Godø 1986; Szalay et al. 2005; Johnson et al. 2008). The width of the net gape is an important factor in the standardisation of trawl catch rates, as it controls the area of sea floor swept by a demersal trawl and thereby the area over which fish are sampled (Jennings et al. 2001).

Estimating changes in fishing power as a result of innovations that advanced trawling efficiency requires extensive records of catch rates that span important gear transitions and emanate from spatially-explicit areas (e.g. Engelhard 2008). Such records may be difficult or impossible to collate in many trawled regions of the world. Without these data, unquantified advances in fishing power or changes in selectivity can be avoided by careful standardisation of trawl gear and methods, imitating the original fishing performance. Revisiting historical survey sites and quantifying change by conducting repeat surveys is not an unusual idea in ecology (Dolman and Sutherland 1992; Simkanin et al. 2005; Chen et al. 2009; Stoner et al. 2012). However, few such experiments have been performed in the logistically challenging and costly realm of marine trawl surveys.

One such example is that by McHugh et al. (2011), who revisited two sites off the south-east coast of England that had been surveyed during 1913–1922 and repeated trawl surveys in 2008–2009. They used an otter trawl that was of the same size and similar mesh to that of the historical gear. Contrasting the two periods, they investigated changes in community

composition and size frequencies of trawl-caught fish. In another example, Andrew et al. (1997) and Graham et al. (2001) report on a 1996/1997 re-survey of the upper continental slope trawling grounds off New South Wales in Australia, 20 years after they were surveyed using the same vessel and similar gear during early stages of commercial exploitation.

The widespread use of otter trawling technology followed its innovation in Granton, Scotland, in 1894 (Cunningham 1896). The rapid adoption of steam power on purpose-built trawl vessels in the late 1880s and early 1890s (Edwards 1909) released vessels from their reliance on adequate winds and increased their fishing power (Garstang 1900). Yet difficulty with handling massive beams on board meant that the size of the beam trawls could not easily expand to take advantage of the excess engine power. In 1894, Mr. Scott of Granton patented new trawl devices that solved this problem (Cunningham 1896). Instead of a stout wooden beam, he employed a set of rectangular 'otter boards', which acted as a pair of underwater kites, pulling the leading edges of the net outwards as they dragged across the sea floor (Cunningham 1896). Without the requirement for a beam and trawl heads, the limit set by their bulk was removed and the size of nets could expand to match the towing power of the vessel. The transformation from beam to otter trawling was so drastic, that in 1899, when Fulton (1901) wanted to compare the efficiency of beam and otter trawls in Scotland, he struggled to find a working beam trawl to use in his experiment. Variants of the Granton gear were used on commercial and survey vessels across different parts of the globe during the early twentieth century, including the UK, Europe, USA, Australia and South Africa.

Because most demersal ecosystems around the world were subject to exploitation for decades to millennia before they were first scientifically sampled by trawl surveys, knowledge of their undisturbed or 'pristine' state is poor (Pinnegar and Engelhard 2008; Schwerdtner Máñez et al. 2014). In this context, the 1897–1904 research trawl surveys, led by John Gilchrist, the 'father' of marine science in South Africa, may be considered unique. They were largely collected beyond the reach of pre-colonial and contemporary (line and seine) fishing efforts and preceded or coincided with initial commercial trawling in the same areas (Currie 2017). Their records therefore provide a rare opportunity to quantify historical reference points and measure the subsequent changes in a temperate demersal fish assemblage, which is of considerable ecological and socio-economic importance in southern Africa. The interest to revisit these historical trawl data and understand the long-term ecological change motivated this study. This paper collates the information required to re-build trawl gear that functionally replicates the fishing power and selectivity of the Granton trawl gear used in South Africa's 1897–1904 trawl surveys. The building of such replica trawl gear and application in an ecological experiment has been achieved (see Currie 2017).

Our approach was to break down the trawl gear into component parts, outline the relevant information contained in literature and summarise the specifics deduced for the gear used onboard the Pieter Faure. Where relevant, the development of trawling technology from the study period and its fishing performance relative to adjacent periods and modern trawl technology is considered. As noted above, very similar Granton trawl technology was used in several regions across the globe in the late 19th and/or early twentieth century. The information provided in this study is therefore of value to investigators of historical trawl records across those global regions.

Methods

Information on the design, dimensions and materials of trawl gear and their operation was gathered from historical literature, photographs and expertise in the trawl industry. The literature included the government reports that detail the Pieter Faure surveys (Department of Agriculture 1898; Department of Agriculture 1899; Department of Agriculture 1900; Department of Agriculture 1901; Department of Agriculture 1902; Department of Agriculture 1903; Department of Agriculture 1904; Department of Agriculture 1905). Early otter trawling developed in the UK (Cunningham 1896) and the Pieter Faure was built in Glasgow, Scotland (Department of Agriculture 1896). As much of the relevant literature was not available in South Africa, it was accessed via correspondence with UK libraries and a visit (by JC) to the Centre for Environment, Fisheries and Aquaculture Science library in Lowestoft.

Additional vessel-specific information was obtained from photographs housed by the Department of Agriculture, Forestry and Fisheries (DAFF) Communications Archive Photo Library, in Cape Town, South Africa. To measure sizes of gear components from historical photographs, the images were scaled using three-dimensional (3D) modelling software, Sketchup Make (version 14, 2014). The software allows one to align axes of three orthogonal dimensions with those of an object in the photograph, typically to reconstruct a 3D model of the object. Thereafter, a known length is used to scale the model (image). In this case, the known width and length of the vessel were used, as well as approximate heights of men appearing in the photographs. Following these procedures, the trawl doors and components of the net could be scaled and their dimensions were measured using the tape-measure tool in Sketchup Make. Mean mesh size was estimated by measuring the four sides of 10 independent codend meshes facing the photographer.

The accuracy of the applied method was difficult to assess without precisely known dimensions of objects in the photographs that could verify the scaling procedure. One difficulty

of applying this method was the curved nature of the ship and identifying truly parallel lines that could be used to align the guides that determine the orthogonal dimensions of the model. However, the heights of men, along with other visible items such as the life-ring, provided diagnostic features used to verify that photographs were approximately correctly scaled. In this way, we expect that dimensions of objects on a photograph of the entire vessel were within ~ 20 cm and those in a photograph of the codend within ~ 0.5 cm of their true size. The average height of men born in Great Britain between 1860 and 1880 (165–170 cm; Hatton 2013) was used as a reference.

Maps scanned from the government reports that detailed the trawl survey results (Department of Agriculture 1899) were used to examine historical towing speeds. The digital images were geo-referenced using a second order polynomial transformation applied in QGIS (QGIS Development Team 2015). As coordinates were not included on these maps, prominent landmarks, such as headlands, river mouths or islets were used as ground control points. The control points were matched on a high resolution outline of the South African coastline, projected in the World Geodetic System (WGS84). The geo-referenced maps were re-projected in the South African Coordinate Reference System, choosing an appropriate longitude zone closest to the trawl location. The lengths of the trawl tracks were then measured using the distance measure tool in QGIS. The speed was calculated as the distance divided by the duration of the trawl. Twelve tracks that were charted and had duration information (start- and end-times) could be used to calculate mean speeds in this way.

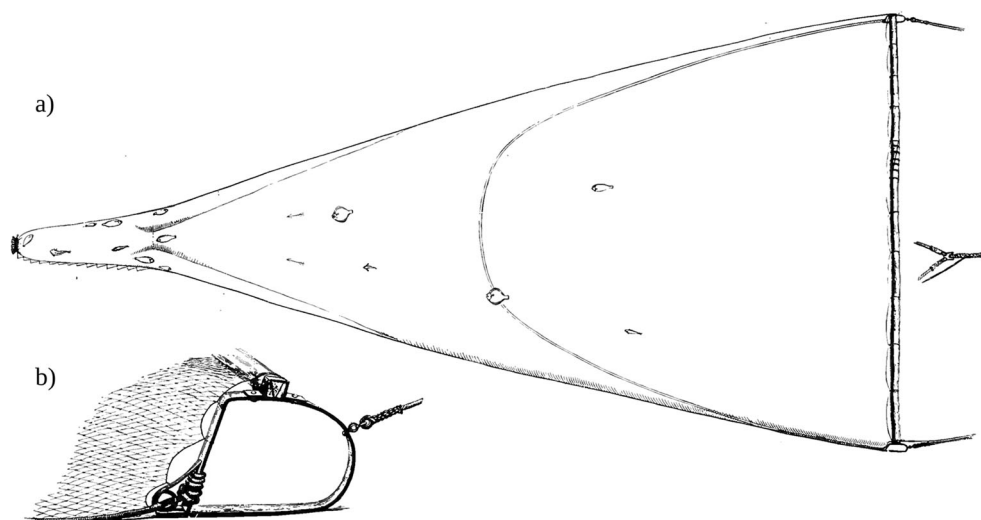
Availability of data and material The datasets supporting the conclusions of this article are included within the article's supplementary files.

Results and discussion

Development of the 'Granton' otter trawl

Late nineteenth-century beam trawls were the precursor to the first 'Granton' otter trawls. Therefore, it is informative to briefly examine the former. The use of beam trawls towed by sailing smacks (traditional fishing boats) was a common fishing method in many parts of the UK by the early 1800s and expanded throughout Britain and the North Sea during the nineteenth century (Robinson 2000; Engelhard 2008). In the late nineteenth century, a Scottish beam trawl typically consisted of a triangular purse-shaped net, with the mouth held open by a straight wooden beam (up to 16.5 m long) and a metal 'trawl-head' on either side that acted as a sled to keep the beam ~ 1.1 m above the seafloor (Fig. 1; Holdsworth 1874; M'Intosh 1895). From the trawl heads, the net would

Fig. 1 A beam trawl as used on the sailing smacks on the east coast of England during the late 1800s, showing a) a vertical view of the entire net and beam and b) greater detail of the trawl 'head' or 'shoe' to which the beam, net and trawl warps were attached. Adapted from Holdsworth (1874), which is in the public domain



narrow to the codend, while the ground-rope (up to 37.8 m in length) would curve far back under the roof ('square') of the net. These trawl nets were up to 36 m in length (M'Intosh 1895).

The fishing power of sail-powered beam trawls was limited: Firstly, they were reliant on the weather (wind) to power their trawling activity, and secondly, the width (size) of their net was constricted by the length of beam that could safely be managed and stowed on board vessels (Heape 1887; Edwards 1909). The introduction of steam powered trawl vessels in the late 1880s and early 1890s released the fleets from their reliance on wind power (Edwards 1909). The fishing power of steam-driven beam trawlers in 1884 was estimated to be about four times greater than that of the sailing smacks a few years prior (Garstang 1900). Despite the improved and excess power source from steam, problems with handling the large beams on board were a hindrance to expanding the size of nets further (Edwards 1909).

Mr. Scott of Granton patented new trawling apparatus in 1894, which circumvented the requirement of a beam (Cunningham 1896). Instead a set of rectangular 'otter boards' were used to hold the net open, heralding the start of 'otter trawling'. The design of the first commercially employed 'otter' or 'Granton' trawls were essentially beam trawl nets attached to otter boards (Fig. 2; Cunningham 1896; Kyle 1903; Edwards 1909). One documented improvement was the addition of wings to the square of the net, in order to accommodate the backward curve of the headline when under tow. The addition was made within the first year or two after Scott's Granton trawls were introduced (Fulton 1901; Davis 1927). Many skippers applied the otter trawl concept but avoided using the patented parts and their associated royalties (Cunningham 1896).

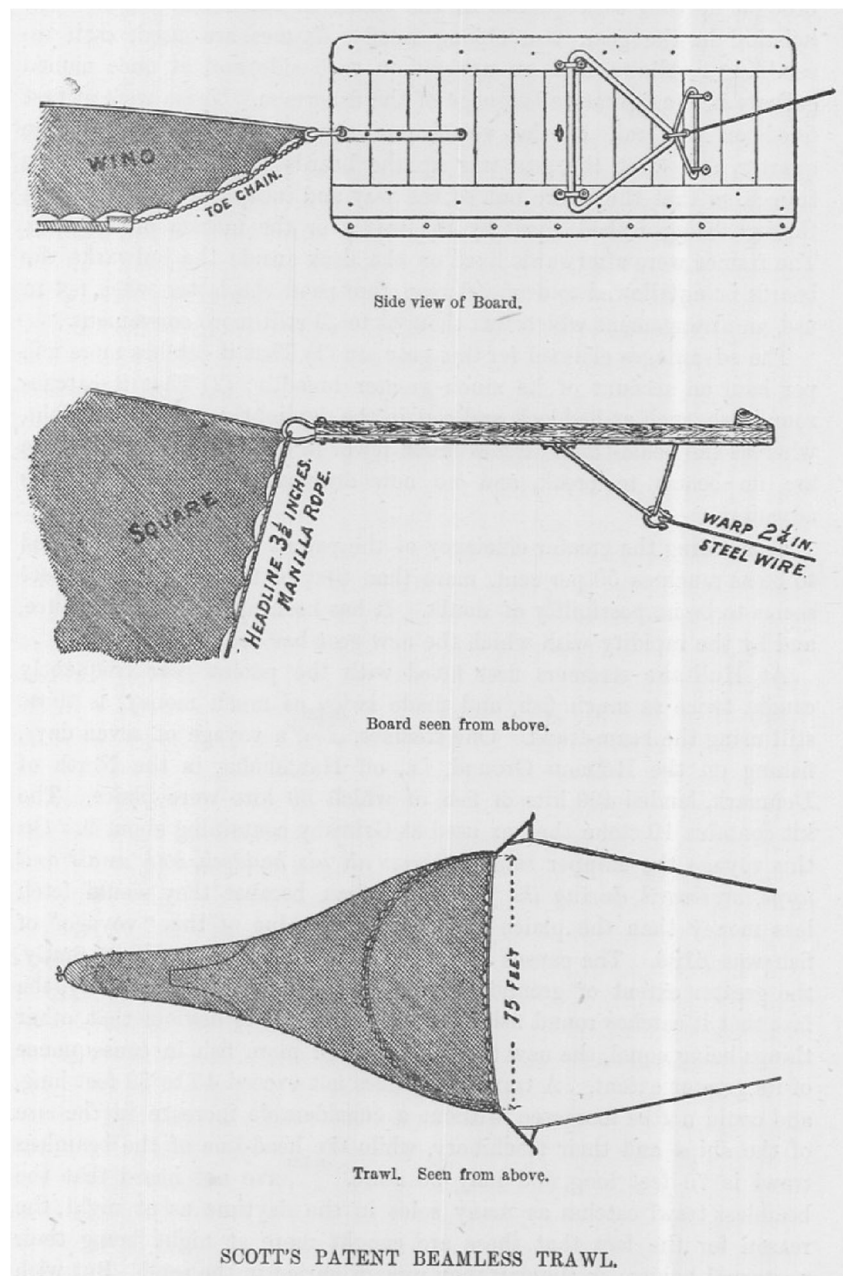
The Granton otter trawl represented a major advance in fishing technology. Without a beam, the headline could rise higher off the sea floor and the dimensions of the net could

expand to match the greater towing power available from steam engines, thereby increasing catches (Garstang 1900). Garstang (1900) estimated that the fishing power of one steam otter trawler in 1898 was equivalent to eight sail-powered beam trawlers in the 1880s and two steam-powered beam trawlers from 1884. The improved catch rates resulted in a rapid expansion of the new otter trawling technology throughout Britain's fishing ports and across the trawling regions globally. This technology reached South Africa in 1897 with the newly commissioned, Scottish-built SS Pieter Faure.

The next major innovation in trawling gear took place in the early 1920s in France, with the introduction of Vigneron-Dahl gear, named after its inventors (Hickling 1931; Le Gall 1931). The critical modification was the addition of 'bridles' or 'sweeps', which were rope or cable extensions that separated the otter boards from the wings of the net. The otter boards and bridles, which were now further apart and ahead of the wings, caused a mud plume and herded fish inwards towards the mouth, thereby expanding the effective net width without increasing the size and drag of the actual net (Hickling 1931). In addition, the net was designed to have a higher-opening headline that was buoyed with floats (Hickling 1931). These changes were highly effective for increasing catches of many 'roundfish' (taxa other than flatfish), including cod (*Gadus morhua*) and hake (*Merluccius merluccius*; Hickling 1931; Margetts 1949), driving its rapid adoption across the world.

Hickling (1931) compared monthly commercial landings made with Granton trawls and the Vigneron-Dahl gear in Scotland and Ireland in 1923 and 1924. He showed that the latter gear tended to catch more fish, sometimes twice as much as the former, but suggested that this advantage related mainly to hake catches and was pronounced when dense schools of smaller hake were present on the fishing grounds. Bowman (1932) compared the efficacy of the two types of gears for catching haddock (*Melanogrammus aeglefinus*), using scientific survey and observer data from commercial vessels. His

Fig. 2 The original otter trawl gear as patented by Mr. Scott of Granton in 1894. Adapted from Cunningham (1896), which is in the public domain



results suggested no difference in size selectivity between the nets but that Vigneron-Dahl gear caught about 50% more haddock than the Granton gear did per unit of time trawling. Wimpenny (1953) suggested that the Vigneron-Dahl modification increased plaice (*Pleuronectes platessa*) catches by at least 25%.

Minor innovations took place between the technological leaps from beam to (Granton) otter trawls and from Granton trawls to Vigneron-Dahl gear, likely driving a gradual creep in fishing power between the late 1890s and early 1920s. The addition of wings to the Granton trawl took place almost immediately after its commercial adoption (Fulton 1901; Davis 1927). After the First World War, innovations were made in

the ground-rope (Wimpenny 1953): Rollers allowed nets to traverse rougher grounds previously inaccessible and 'tickler chains' ahead of the ground-rope acted to flush fish from the sediments, some of which might have escaped capture below the advancing ground-rope. Part of the technological creep prior to these and the Vigneron-Dahl innovations was likely fuelled by improving steam engines and power output, as larger nets were enabled by greater engine power (Gibbs 1922).

Focusing on cod and plaice catches respectively, Engelhard (2008) calculated the fishing power of southern North Sea trawlers in 1906–1914 to have varied ~10–15 times and ~4–5 times that of an 1880s sailing smack. The

work by Engelhard (2008), together with the calculations made by Garstang (1900), suggest that the fishing power of early twentieth century steam trawlers fishing Granton trawls was approximately 26% (for cod) and 29% (for plaice) compared to that of 1980s motor trawlers, while modern twin-beam trawls were up to 30 times more effective at catching plaice.

Trawling speed

Once the net sizes could expand beyond the limits set by the beam trawl, engine power became the factor limiting the size of trawl nets. Larger catches were possible with bigger nets, but their increased drag had to be balanced with the spreading force generated by the otter boards and the drag of both had to be kept within the towing power of the vessel.

Trawling speeds vary among different vessels and trawl gear, and the speed of a single vessel can change among substrate types or in varying conditions of weather or currents (M'Intosh 1895; Dealeris et al. 1989). Modern demersal trawlers commonly attain speeds of $1.5\text{--}2.1\text{ m}\cdot\text{s}^{-1}$ (3–4 knots) and higher (Dahm et al. 2002; Weinberg 2003). Early steam trawlers were less powerful and slower towing speeds are indicated by the literature. The average speed of beam trawls towed by steam vessels in the late nineteenth century is recorded as $1.29\text{ m}\cdot\text{s}^{-1}$ (2.5 knots), although higher speeds could be attained on muddy grounds (M'Intosh 1895). In 1900, the speed of three otter trawlers was measured and their average speed was calculated to be $1.36\text{ m}\cdot\text{s}^{-1}$ (2.64 knots; Fulton 1901). Kyle (1903) reported the average speed of a towed otter trawl as $1.29\text{ m}\cdot\text{s}^{-1}$ (2.5 knots) and that of a beam trawl as $1.03\text{ m}\cdot\text{s}^{-1}$ (2 knots). On the SS Huxley, which was the first research vessel employed by the UK's Centre for Environment, Fisheries and Aquaculture, measurements during 135 otter trawl hauls resulted in a towing speed range of $1.03\text{--}1.49\text{ m}\cdot\text{s}^{-1}$ (2–2.9 knots), with an average and mode of about $1.18\text{ m}\cdot\text{s}^{-1}$ (2.3 knots; Garstang 1905). The Huxley was of a similar vessel and engine size to that of the Pieter Faure and the range of trawling speeds measured by Garstang (1905; 2–2.9 knots) capture the figures recorded by other authors during the early Granton trawl era.

Historically, trawls were frequently towed on a curved or circular track. As a result, comparing start and end locations to calculate the towing distances is not reliable. Fortunately, Gilchrist provided a handful of detailed maps on which he traced the trawl tracks of the Pieter Faure (Online Resource 1; Department of Agriculture 1899). From the 12 trawl tracks that had a duration recorded and could be measured off geo-referenced maps, we estimated the mean speed to have been $1.35\text{ m}\cdot\text{s}^{-1}$ (2.62 knots; interquartile range of 2.15–3.13 knots). These results are congruent with, if slightly higher, than the speeds reported from the literature above. Therefore, we assume the Pieter Faure towing speed

was approximately $1.35\text{ m}\cdot\text{s}^{-1}$. While this figure may be used to standardise catches from the Pieter Faure surveys, we recommend that investigators assess the sensitivity of their results to the bounds provided by the interquartile range of $1.11\text{--}1.61\text{ m}\cdot\text{s}^{-1}$ (2.15–3.13 knots).

Net design

The shape and dimensions of the net are governed by an interplay of multiple factors. The perimeter of the mouth is prescribed by the lengths of the headline and ground-rope. The outward pull exerted by the otter boards acts to widen the net (and frequently reduce its vertical gape), but is countered by the drag of the net, which in turn is affected by factors such as mesh sizes and twine thickness (FAO 1974; personal communication Noel Less, Viking Fishing). Such components (net materials; headline; ground-rope; meshes; otter boards; warps) are discussed in separate sections below. However, the general shape and behaviour of the net will additionally be affected by its design, specifically the shape and dimensions of the various panels from which it is constructed and the way in which they are connected.

In the absence of specific design plans for the trawl used on the Pieter Faure, the best alternative was to investigate the designs of trawls constructed in the same era and region. Net plans—design drawings that provide details on the number of meshes and shapes of panels making up the net—were not found from the initial years of otter trawling. The earliest detailed description and plans of an otter trawl that we could locate were those of a ‘commercial trawl net’ by Kyle (1903; Fig. 3). This was the same net outlined by Garstang (1905) and used in 1902–1903 surveys on the British research vessel, the SS Huxley.

Different to modern gear, this historical net included a type of non-return valve ahead of the codend, intended to prevent fish from escaping once they were in the codend. It consisted of a funnel created by blind-ending pockets laced between the upper and lower surfaces of the net, as well as a loose piece of netting that acted as a lid, called the ‘flapper’ (Fig. 3; Kyle 1903; Garner 1956). The flapper and pockets were present in beam trawls in the nineteenth century (Holdsworth 1874) and their use continued decades into the era of otter trawling (Davis 1927; Garner 1956).

As is still in use today, an extra barrier was included on the underside of the codend, to protect the net from abrasion as it dragged over the sea floor. These ‘chafers’ or ‘rubbers’ commonly consist of a panel of double twine meshes nowadays, whereas historically they were made of overlapping sections of old netting (Holdsworth 1874; Kyle 1903). In photographs of the Pieter Faure codend, loose pieces of chafer netting can be identified (Fig. 4; Online Resource 1). Visible on the same photographs are the ropes that form the belly lines, which are the seams along which the top and

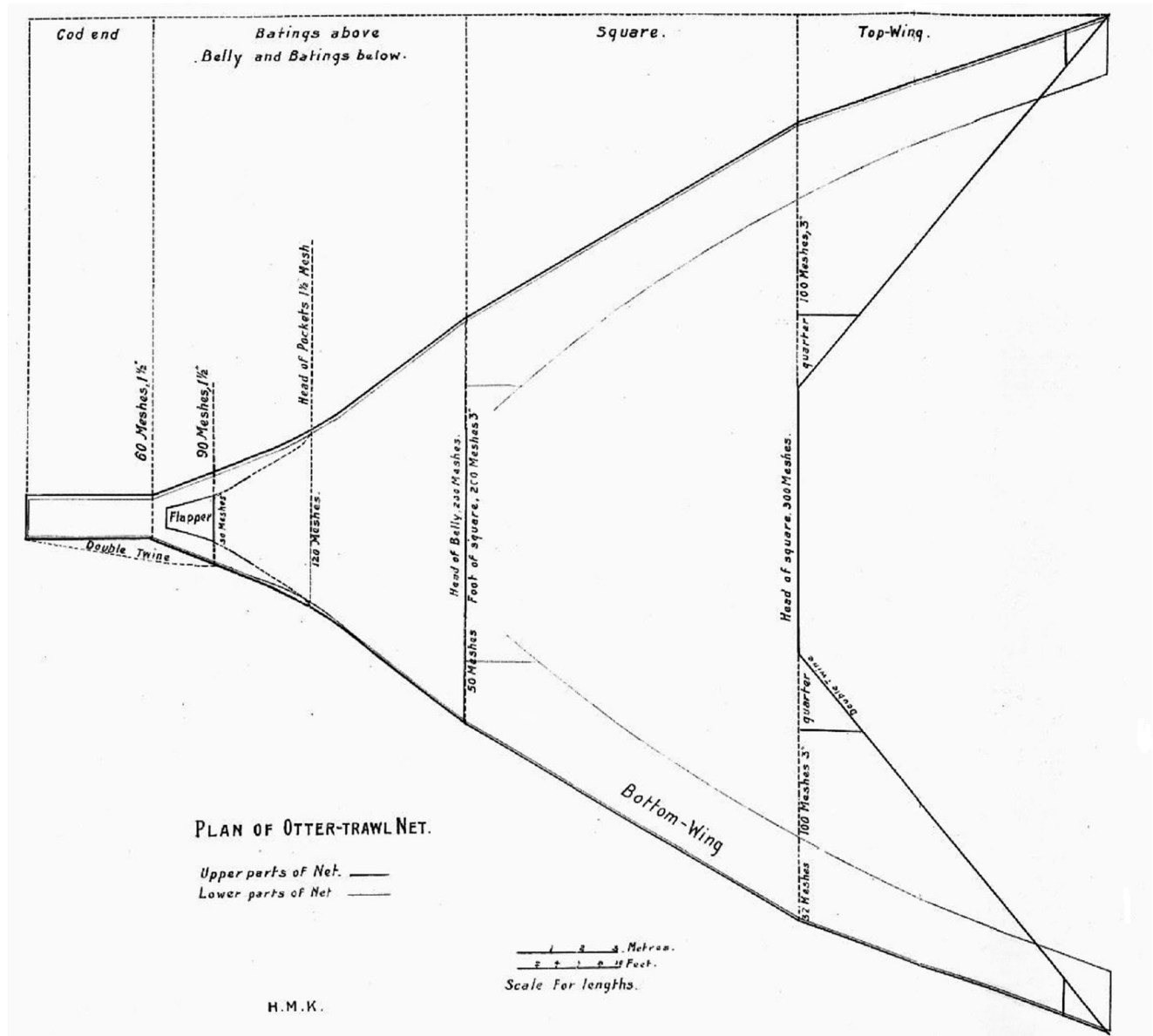


Fig. 3 One of the earliest known plans of a Granton otter trawl (Kyle 1903). Reproduced with permission from the copyright holder, Cambridge University Press

bottom halves of the trawl net are laced together (Garner 1956). From the scaled photograph, we estimated these ropes to be about 20 mm in diameter, which is thicker than the 16 mm diameter (2-in. circumference) reported by Kyle (1903).

How much trawl technology might have evolved between the time that the Pieter Faure sailed with her crew from Glasgow in 1897, and 1902/1903, when Kyle (1903) wrote his paper and the Huxley was fitted with the net specified in those plans (Garstang 1905), is unknown, but expected to be minimal. The addition of wings had taken place before this period (Fulton 1901; Davis 1927). Other than that, evidence of significant changes in net design were not found until the introduction of rollers and tickler chains

after the First World War, and the spread of Vigneron-Dahl modifications in the 1920s (Hickling 1931; Wimpenny 1953). In the interim, skippers made small adjustments to improve their gear (Kyle 1903). As such, trawl gear of 1902, for which the design is known, likely included slight advancements over the net technology that had been brought to South Africa in 1897. Nonetheless, the net used on the Pieter Faure must have been very similar to that described by Kyle (1903) and employed on the Huxley. In a recent reconstruction of the Pieter Faure net (Currie 2017), the plans provided by Kyle (1903) were followed, adjusting specific components according to the details gleaned from photographs of, and from on board, the vessel (Figs. 4, 6, 7; Online Resource 1).



Fig. 4 Deck scene from the Pieter Faure, showing the full codend of the trawl. Mesh sizes and twine thickness were estimated from this photograph. DAFF Communications Archive Photo Library

Net materials

In the UK, the use of hemp (*Cannabis sativa*) twine to construct large trawl nets was largely replaced by the use of Manila hemp (*Musa textilis*) during the latter parts of the nineteenth century (Kyle 1903; Edwards 1909). Manila was in turn replaced with hardier synthetic twines in the mid twentieth century (Garner 1956; von Brandt and Garrothers 1965). Both Manila and hemp were treated with tar before being used in trawl nets, to reduce the ingress of sediment and water absorption and prolong their lifetime (Kyle 1903; Davis 1927). The addition of tar also acts to increase the stiffness of the rope (personal communication Louis Jacobsz, CapeNetting) and reduces its specific gravity (coal tar, Stockholm tar and bitumen all have specific gravities > 1 but lower than that of Manila).

Different twines frequently result in different selectivity factors, believed to be due to properties such as flexibility (Clark and Jensen 1963; McCracken 1963; Lowry and Robertson 1996) and extensibility (elasticity) of the fibre used to construct the net (von Brandt 1963; Clark and Fritz 1963). In addition, the specific gravity of the twine material may influence the fishing performance, as it affects the buoyancy of the net panels, thereby the shape of the net and its contact with the sea floor.

Twine thickness also plays a significant role in the selectivity of a net (Sala et al. 2007), with thicker twines shown to have a lower selectivity (retain more fish), likely due to their reduced flexibility allowing fewer fish to escape (Lowry and Robertson 1996; Sala et al. 2007; Graham et al. 2009). The twine diameter of the Pieter Faure net was estimated from photographs, as reported in the *Net meshes* section below.

The Pieter Faure net was made of tarred Manila, as suggested in the literature and supported by the images of the net (Fig. 4; Online Resource 1). Because synthetic twines have subsequently replaced the use of Manila in the construction of

trawl nets, sufficient Manila twine of appropriate thickness was not available for re-construction of the entire net. A synthetic alternative with similar properties therefore had to be found to supplement the available Manila.

Considering the properties of common twines relative to those of Manila (Online Resource 1), a mixture of polyester and polyethylene was suggested by a netting manufacturer, as a rope that would exhibit a fishing performance similar to that of Manila (personal communication Louis Jacobsz, CapeNetting). Polyester has the same specific gravity in water as Manila (1.38), whereas the other synthetic twines are lighter. However, polyester fibres are soft compared to the relatively stiff fibres of Manila. Polyethylene fibres produce a far stiffer rope, similar to that of Manila, yet have a relatively low specific gravity (0.95). To produce a rope that had similar properties to Manila, polyethylene and polyester were combined in equal proportions, resulting in a specific gravity and flexibility between those of its two components.

Neither polyester nor polyethylene required the preservation advantages of tarring, however the addition of tar also influences the stiffness and specific gravity of the rope. To simulate these effects, the net meshes were tarred, whether made of Manila or the synthetic alternative. This was achieved by soaking them in a bitumen solution (bitumen and petroleum solvent) for 30 min before they were air-dried (personal communication Andre Tuit, Southern Ropes).

Headline

The size of an otter trawl is traditionally defined by the length of its headline, which prescribes the width of the mouth. Cunningham (1896) reports that Mr. Scott's early otter trawls had a headline length of 22.9 m (75 ft). As the sizes of nets generally grew with the power of steam trawlers (Fulton 1901; Edwards 1909), it is informative to look at the nets used on vessels of similar size and engine power to the Pieter Faure. Unfortunately, net details are not available for many vessels from the same era. The SS Huxley (35.3 m and 206 gross tons) was a similar size to the Pieter Faure (35.1 m and 176 gross tons) and both had similar-sized triple-expansion steam engines (52 versus 50 nominal Hp respectively). The otter trawl used on the SS Huxley in 1902/1903 had a headline length of 27.4 m (90 ft.; Garstang 1905).

In 1914, the Australian government ordered three new 'deep sea trawlers' (Jacobsen 2010). Two of these vessels were sister ships (the SS Koraaga and SS Gunundaal) and were the same length as the Pieter Faure, but had heavier gross tonnages of 220 tons. They also had triple-expansion steam engines and although we found no information on the power of these, they would certainly have been as, or more, powerful than those fitted to the Pieter Faure 18 years before. The otter trawls on these two vessels also had headline lengths of 27.4 m (90 ft.; Jacobsen 2010). The fact that slightly larger

vessels used otter trawls with a headline length of 27.4 m, provides compelling evidence to support the argument that the Pieter Faure would not have been using a net much larger than this.

Commercial trawlers in Scotland were using headline lengths of up to 42.7 m by 1900 (140 ft.; Fulton 1901), even though shorter lengths of between 27.4 and 30.5 m were popular well into the twentieth century (Todd 1911; Davis 1927). The longer headlines reported by Fulton (1901) were likely fished from larger and more powerful vessels than the Pieter Faure. M'Intosh (1895) reported that modern steam trawlers in Scotland at that time were up to 36.6 m 'between the perpendiculars', which implies a total length notably greater than the 30.1-m Pieter Faure built 2 years later. He also mentions that the engine sizes ranged up to 65 nominal Hp, whereas that of the Pieter Faure was 50 nominal Hp.

Trawl headlines in Britain were predominantly made of Manila for several decades, starting in the late 1800s (Cunningham 1896; Garner 1956). The diameter of ropes used was typically between 24 and 32 mm (3 and 4 in. circumference respectively; Cunningham 1896; Kyle 1903; Davis 1927; Garner 1956).

Gilchrist did not specify the headline length of the trawl net used on the Pieter Faure. He did, however, appreciate the importance of keeping the size of the trawl consistent for comparative purposes and in 1898 suggested that the width of the mouth was 'about 80 ft' (24.4 m; Department of Agriculture 1899). Gilchrist certainly and unwittingly overestimated the width of his net at that time, as neither he nor his colleagues (nor trawlermen) in Britain appreciated the extent to which the headline curved, until experiments were performed 3 years later to examine this point (Fulton 1901). At the time, net-makers allowed for one-third of the headline length to form the semi-circle between doors (Fulton 1901), whereas the results of those experiments suggested it to be about one-half. If Gilchrist in 1898, based his net width estimate on the same assumption that net-makers of Scotland did in 1901, then this would imply a 36.6 m (120 ft) headline, which serves as an upper bound to what the size of the Pieter Faure net might have been. Assuming that Gilchrist expected a minimum reduction between headline length and mouth width of at least 10%, a lower bound estimate of the headline is 26.8 m. Based on the above reasoning we are confident that the headline on the Pieter Faure trawl was between 26.8 and 36.6 m long (88 and 120 ft. respectively).

The headline was 'marled' (connected) directly to the square and wing meshes as shown in Fig. 5a (Kyle 1903; Davis 1927), which is consistent with sections of the headline visible in Fig. 6. Using the scaled photograph in Fig. 6, the Pieter Faure headline is estimated to be about 30 mm in diameter, although an accurate measure is precluded by the resolution of the image. The thickness of headlines at the time varied between 24.3 and 28.3 mm (3 to 3.5 in. circumference; Kyle

1903). Thus, a piece of Manila rope of 28 mm diameter and a 27.4 m (90 ft) length was used for reconstruction of the Pieter Faure net. Analyses using net-width in the swept-area standardisation of catches, should however include sensitivity analyses for a range of 26.8–36.6 m (88–120 ft).

Ground-rope

A standard historical ground-rope consisted of an old 'wire warp' (steel cable), 16 to 24 mm in diameter (2.5 to 3 in. circumference), covered with old netting material and then rounded with a Manila rope to a diameter of 81 to 97 mm (circumference of 10 to 12 in.; Kyle 1903; Davis 1927). The method of attachment between ground-rope and net (belly and wings) followed the traditions of beam trawls, whereby a bolsh line (or balch line) was used to connect the meshes of the net to the foot-rope, as in Fig. 5b (Kyle 1903; Davis 1927).

Although Gilchrist did not specify the length of the ground-rope used on the Pieter Faure, a commonly used commercial trawl at the turn of the century and early 1900s was one with a 27.4 m (90 ft) headline and a 38.1 m (125 ft) ground-rope (Kyle 1903; Garstang 1905; Davis 1927). Ground-ropes of 36.6 m (120 ft) or slightly longer seem to have been common even with earlier and lesser-width beam (M'Intosh 1895) and otter trawls (Cunningham 1896). The ground-rope was frequently made of three sections, a bosom of about 6.1 m (20 ft) in the middle and a wing section either side (Kyle 1903; Davis 1927).

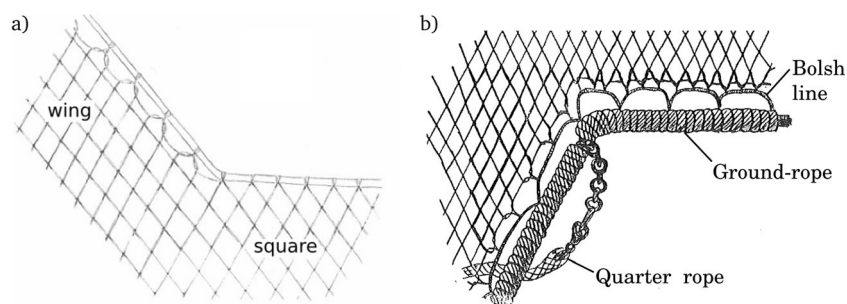
The ground-rope used on the Pieter Faure is partly visible on the photograph of the vessel (Fig. 6), which shows it to be consistent with the description provided above. The larger gaps between the bolsh line and ground-rope (compared to those of the mesh) are clearly visible in the shadow cast on the side of the vessel in Fig. 6. Using the scaled photograph, the diameter of the ground-rope was estimated to be about 100 mm.

In our reconstruction of the Pieter Faure net, a 38.1 m (125 ft) ground-rope was assumed, as per the trawl plan by Kyle (1903). The ground-rope consisted of three sections: a central bosom of 6.1 m, shackled to wing sections either side (Kyle 1903; Davis 1927). We used a 20-mm fibre-core cable, rounded with 10 mm diameter tarred Manila rope (in place of old Manila netting) and then served (rounded) with a 28 mm Manila rope. The result was a ~96 mm diameter ground-rope that should be very similar to those used historically on soft trawling grounds, both in South Africa and abroad.

Net meshes

Alward (1932) reports that fishermen had historically braided nets at sea, using finger-widths to measure the meshes, starting with two fingers at the codend, increasing to three, four and five fingers towards the mouth of the net. When nets were later made ashore, often by women who had smaller fingers,

Fig. 5 Drawings depicting the method of attachments between net meshes and a) the headline (Kyle, 1903), and b) the ground-rope, via a bolsh line (Davis 1927). a) Adapted with permission from the copyright holder, the Cambridge University Press; b) adapted under the Open Government Licence, UK



wooden gauges known as ‘spools’ were introduced to standardise mesh sizes (Alward 1932). The modern convention (in South Africa and many other countries) is to describe the length between opposite knots of a longitudinally stretched mesh. Because it is of importance to fisheries regulations, this measure usually applies to the distance within the mesh, excluding the knots. Historically mesh regulations were of less concern or absent and mesh sizes were typically measured between the centres of knots. To remain consistent with the historical reconstruction in this paper, we refer to the longitudinally stretched mesh size between the centres of knots unless specified otherwise.

Differences in the way authors (and fishers) referred to mesh sizes can cause confusion, as the number of sides included in the measurement could vary. For example, a ‘4-in. mesh’ might refer to one that was 4 in. between opposite knots when fully stretched longitudinally (similar to today’s convention), or it could imply a mesh of which a single side was 4 in. (thus 8 in. stretched longitudinally), or less frequently, it could even refer to the circumference of a mesh where each side between adjacent knots measured 1 in. (Davis 1927). Fortunately some authors specified which measure they were using, by calling it 4-in. ‘bar’ for example (Davis 1927), or 4-

in. ‘square’ (Holt 1895), both of which specify that the length referred to one side between adjacent knots.

Where quoted measurements can be interpreted with certainty in the historical literature, the most commonly referenced codend mesh size used in both beam and otter trawls seems to be 76 mm (3 in. or 1.5 in. “bar”; Holdsworth 1874; Heape 1887; Holt 1895; M’Intosh 1895; Kyle 1903; Aflalo 1904; Davis 1927; Alward 1932; March 1953). There is however, some variability around this figure: one author suggests that codend meshes varied between 76 and 127 mm (1.5 and 2.5 in. “bar”; Alward 1932), whereas other authors recorded codend meshes as small as 70 mm (Todd 1911), 64 mm (1.25 in. “bar”; Fulton 1901) and even 38 mm (0.75 in. “bar”; Holt 1895).

Using a scaled photograph of the Pieter Faure codend (Fig. 4), the meshes were estimated to be 48 mm ‘bar’ ($\pm$ S.E. 0.6 mm), which implies a $\sim$ 96-mm stretched mesh size. The diameter of the codend twine estimated from the same scaled photograph was 6 mm. As the exact location of men standing in the photograph (relative to the surface of the net) and their true height is not known, a level of unquantified uncertainty remains around the scaling of the photograph and these estimates. Nonetheless, the historical photographs provide valuable evidence to ensure that gear dimensions are close to those originally used on the Pieter Faure.

The images of the codend (Fig. 4; Online Resource 1) show that its meshes were made from a single twine, despite reports that codends were frequently braided with double twine (Kyle 1903; Todd 1911; Davis 1927; Garner 1956). Based on the evidence from the plan by Kyle (1903) and these photographs, a 6-mm single (Manila) rope was used for our reconstruction of the Pieter Faure codend and extension piece ahead of it. Thinner synthetic twines (4 and 5 mm) were used in the remainder of the net (Online Resource 3). The mesh sizes were braided as 100 mm between opposing knots for the codend and extension piece, whereas the remainder of the net was made of 150 mm stretched meshes, as per the plan by Kyle (1903).

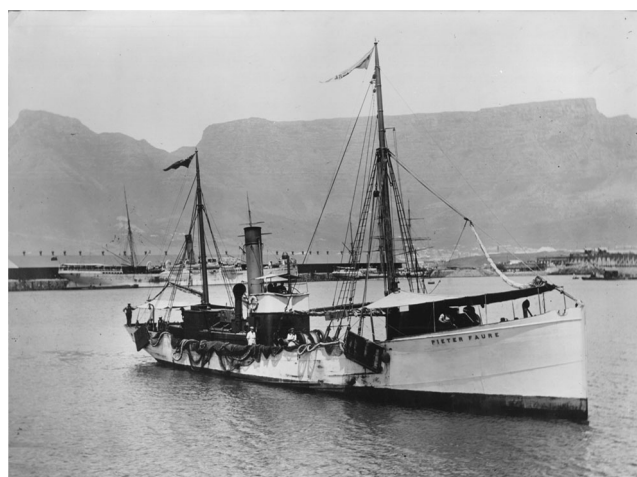


Fig. 6 Photograph of the Pieter Faure in Table Bay, Cape Town. The date is unknown, however some of the crew visible can be matched to another photograph (Fig. 7) that includes John Gilchrist on deck, suggesting that this suite of photographs was taken between 1897 and 1906. DAFF Communications Archive Photo Library

Otter boards

The otter boards used historically were flat, rectangular wooden boards, attached to a heavy metal ‘shoe’ or brace. The

initial patented doors introduced by Mr. Scott consisted of heavy timber framed with steel and had a ring extending from the back end to which both headline and foot-rope were connected (Fig. 2; Cunningham 1896). The ring at the back of the board was soon discarded and instead the headline and ground-rope were shackled separately to the back edge of the board (Kyle 1903; Gibbs 1922). Part of the patent were stout triangular metal brackets to which the trawl warps were shackled (Fig. 2). These brackets remained popular to recent decades, although some fishers used a set of four chains attached closer to the corners of the trawl doors to avoid the patent (Cunningham 1896; Kyle 1903).

Dimensions and weights of otter doors documented by authors during the period relevant to this investigation are listed in Table 1. The sizes of boards varied substantially, though perhaps not surprisingly, as the board size had to be matched to the net size and vessel power (Jenkins 1920; Graham 1956).

The angle of attack (between the line of forward motion and the vertical plane of the board) is an important setting for the effectiveness and efficiency of otter doors (Garner 1956; FAO 1974). The point of attachment to the triangular brackets (which influences the angle of attack) was approximately one-third of the length of the board from its front edge (Kyle 1903; Jenkins 1920). The historical angle of attack is recorded to have been about 20 degrees (Edwards 1909; Jenkins 1920; it appears the latter author was reproducing information from the former). More recent literature reports angles of attack between 35 and 50 degrees, even though the maximum spreading force for such boards is predicted to be at angles less than 30 degrees and their maximum efficiency at even lower angles (FAO 1974; Patterson and Watts 1986). Modern trawl doors used with nets of similar size to the historical gear are substantially smaller in surface area than the dimensions listed in Table 1 (personal communication Noel Less, Viking Fishing). It makes sense, therefore, that the larger doors were fished at lower angles of attack than smaller modern doors.

Fortunately the otter boards used on the Pieter Faure were captured in a photograph of the vessel (Fig. 6), from which their dimensions were measured after the image was scaled. The otter boards were estimated to have a length, height and thickness of 2.42, 1.48 and 0.07 m respectively. Figure 6 shows three transverse bars on the Pieter Faure doors, indicative that they used the patent triangle brackets, rather than the chain connections (Kyle 1903). Also visible on this photograph is confirmation that the headline and ground-rope were shackled separately to the (upper and lower) hind edge of the trawl doors.

Our reconstruction of otter boards that would functionally imitate those of the Pieter Faure used dimensions (2.7 by 1.4 by 0.05 m) similar to those estimated from the photograph, but adjusted to be consistent with typical length:height ratios from the literature. They were made of hard wood (resistant to rot),

with a steel frame and brackets. The weight of each door was approximately 400 kg. Their angle of attack was set close to 20 degrees, although adjustable brackets could allow the angle to be modified if necessary. Plans of these trawl doors are provided in Online Resource 3.

Warps

The trawl warps used historically were steel cables similar to fibre-core cables employed today (personal communication Noel Less, Viking Fishing). Their diameter was recorded to be 18.2 mm (2.25 in. circumference; Cunningham 1896), whereas they currently range between 14 and 22 mm on in-shore trawlers in South Africa (personal communication Noel Less, Viking Fishing).

Trawlermen historically let out their warps to roughly three times the depth of water, though this ratio was increased in shallower waters and could be less in deeper waters (Gibbs 1922; Davis 1927). This is the same approach in use by current trawl skippers (personal communication Noel Less, Viking Fishing).

The Pieter Faure cables were captured in photos taken on the deck of the vessel (Fig. 7) and are estimated to have a diameter of 17–18 mm, which is close to the 18.2 mm thickness reported by Cunningham (1896). One might expect trawl warps made of different material (e.g. rope vs steel), or with a markedly different diameter, to behave differently in water (and thereby influence the action of the trawl; Crewe 1964). Considering that the historical (Pieter Faure) warps and those currently used are of similar diameter and materials, any potential differences in the production of wire cables of a century ago and those used now are not expected to have a discernible influence on the shape or efficiency of the trawl.

Operation of historical side-trawls

The salient points of shooting and hauling the trawl on a steam-powered side trawler, such as the Pieter Faure, are briefly described below. Edwards (1909), Davis (1927) and Graham (1956) provide further detail on these gear operations and are the sources from which the below description was gathered. The navigational and fishing operations were completed without any of the electronic devices in use today, but steam-driven winches were employed. The entire process took place off the side of the trawler rather than the stern as in most modern vessels.

Once a decision had been made to shoot the trawl, the ship was brought to a standstill with the trawl doors facing into the wind, so that once the net was released into the water, the vessel would drift away from it. The doors were put over the side and lowered several metres below the surface. Next, the net was thrown into the water, first the codend, followed by the rest of the net. The ground-rope was put over the side and lastly the

Table 1 Dimensions and weights of otter trawl doors as reported in historical literature from the period relevant to the Pieter Faure era

Length (m)	Height (m)	Thickness (cm)	Weight (kg)	Period	Reference
3.05	1.37			1894	Cunningham (1896)
1.83–2.43	1.22			1895/1896	Cunningham (1896)
3.66	1.524			1895	M'Intosh (1895)
3.05–3.20	1.22–1.37			1901	Fulton (1901)
2.74–3.05	1.35–1.37	10.2–12.7	457	1900s	Kyle (1903)
3.05	1.52	7.6–10.2		1900s	Aflalo (1904)
2.44	1.3	6.4		1902	Garstang (1905)
2.44–3.05	1.22–1.52		363–454	1900s	Edwards (1909)
2.44–3.05	1.22–1.52		363–454	1910s	Jenkins (1920)
3.35	1.37		762	1920	Gibbs (1922)

headline was released. If the net and boards looked correctly aligned and clear of the vessel, the engines would be put full speed ahead with the vessel turning in a wide circle towards the side that the trawl was shot (to keep the net clear of the propeller). As the ship picked up speed, the warps were paid out at a



Fig. 7 Deck scene on the Pieter Faure, showing John Gilchrist (front right) and crew taking a break while the trawl is under tow. DAFF Communications Archive Photo Library

rate that kept sufficient tension to spread the trawl doors and avoid fouling the net. Once the correct lengths of warp were paid out, the vessel slowed to its towing speed (2–3 knots). The fore (front) warp was pulled in towards the aft (back) warp and side of the vessel, using a messenger wire and winch, where they were both locked into a towing block. In Fig. 7, the two warps are locked into the towing block and can be seen leaving the side of the vessel. Markers on the warps are also visible in the picture, which were spaced at set intervals to help ensure that the warp lengths could easily be aligned.

As with shooting the trawl, the net had to be hauled on the windward side of the vessel. The towing block was knocked open, which released the fore warp. The engine was set to 'dead slow' and the pull on the fore warp turned the vessel side-on to the trailing trawl net. The warps were then wound up by the winch until the trawl doors arrived at the 'gallows', where they were secured. The quarter ropes (ropes on the outside of the net that connected the middle of the ground-rope to the trawl doors) were loosened from the doors and passed to a winch, which brought in the ground-rope. Once the ground-rope was on board, the remainder of the net was pulled in over the side by hand, until the codend was reached. A special rope, called a becket, would be looped around the codend, and lifted by winch power to heave the codend over the side and suspend it above the deck, before it was untied to release the catch.

The procedure of shooting the net and hauling it back on board has become more mechanised and efficient over time, contributing towards the greatly increased fishing power of modern trawlers (Engelhard 2008). Stern trawlers enabled improved efficiency over side trawlers in this regard (Robinson 2000): The entire net is hauled up the stern ramp on stern trawlers, allowing faster retrieval and the added advantage that the vessel can reposition itself for the next trawl while the codend is being emptied and re-tied. In the use of side trawlers, much of the net remained in the water while the codend was emptied, during which time the vessel could not move to a new position.

In the comparison of commercial catch data, improved efficiencies that reduce the gear handling time (during which the net is not actively fishing) should be considered. The median time between successive trawl hauls on the Pieter Faure, measured from when the net was hauled until it was shot for the next trawl, was 35 min, with the 10th and 90th percentiles ranging 30–56 min (Online Resource 2). In 1903 the Pieter Faure was engaged on a ‘commercial experiment’ to demonstrate the economic viability of trawling from Cape Town. This 5-week period allowed examination of the proportion of total time spent actively trawling (trawl gear in the water). Including the time spent in port between trips and that taken to steam to and from the fishing grounds, the vessel was fishing 26% of its time while engaged in the commercial experiment (Online Resource 2).

Investigations of haul-by-haul survey catches, like those collected on board the Pieter Faure, typically use the durations of trawl hauls to standardise fishing effort and the turnaround (‘handling’) time between successive hauls have little consequence to analyses. The duration of trawls recorded during the Pieter Faure surveys was typically 2–4 h in length (Department of Agriculture 1899; Department of Agriculture 1900; Department of Agriculture 1901; Department of Agriculture 1902; Department of Agriculture 1903; Department of Agriculture 1904; Department of Agriculture 1905).

Conclusion

This work provides a foundation for understanding the gear design and fishing power of (commercial and survey) Granton otter trawls at the turn of the twentieth century. Besides collating knowledge of historical fishing power, the results could help inform investigations of past ecosystem effects of fishing, such as those of demersal trawl impacts on the seafloor (Eigaard et al. 2015) and the resuspension of sediments by passing trawl gear (O’Neill and Ivanović 2016).

The Pieter Faure surveys, for which this gear was used, were exploratory in nature and preceded substantial human impacts on the local demersal ecosystems. We present the information necessary to repeat those historical surveys. This approach was pursued in South Africa, where sites visited by the Pieter Faure approximately 115 years previously were resurveyed with reconstructed trawl gear (Currie 2017). In addition to the information gleaned from extensive archival documents, significant input was gained from experienced individuals in the trawl and net-building industries, underlining the benefits of stakeholder involvement in fisheries research (Mackinson et al. 2011).

Not all details of the historical gear could be resolved, requiring certain assumptions and remaining uncertainties to be considered. Incomplete information on the exact dimensions of the Pieter Faure net and the vessel’s trawling speed will require analyses of the historical catch data to examine the

impact of those uncertainties. We did identify plausible bounds for these variables and their effect on swept-area standardised catches can be calculated. In spite of these challenges, this work provides a blueprint to build trawl gear that will imitate, to a close degree, the fishing power and selectivity of a Granton otter trawl used in the early twentieth century.

The efficacy of early Granton otter trawls was notably greater than their beam trawl predecessors (Garstang 1900), but lower than the Vigneron Dahl modifications that were rapidly adopted during the 1920s (Hickling 1931; Bowman 1932). While quantitative estimates of fishing power over time are available in the cases documented by Engelhard (2008), they cover only two species in the North Sea region. The records (contiguous in time and space) required to quantify temporal changes in fishing power are likely lacking in the majority of cases. Either way, we suggest that the replication of trawl gear and methods will allow greater confidence in comparative results than attempts to standardise catches from different trawl methods and gears.

This study is of relevance beyond South Africa, given that comparable equipment was used widely on scientific and commercial vessels fishing shelf seas off Europe, North America and Australia. Countries that employed similar trawl gear in marine surveys include the UK (SS Huxley; Garstang 1905), the USA (SS Albatross; Alexander et al. 1915; Smith 1921), Norway (SS Michael Sars; Hjort 1914), Netherlands (SS Wodan; Anon 1908; ter Hofstede and Rijnsdorp 2011) and Australia (SS Thetis, FIS Endeavour; Department of Trade and Customs 1909). Building upon the information collated here, repeat trawl surveys could conceivably be developed in various parts of the world, allowing assessment of current versus historical states of marine ecosystems. Our research demonstrates the feasibility of such gear reconstructions and deepens understanding of their historical fishing powers.

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Author’s contributions This manuscript was based on a chapter in JC’s PhD thesis. JC wrote the draft and conducted the analyses. GE provided substantial input to the conception and manuscript structure, contributed text, returned multiple iterations of editorial input and assisted with access to historical literature (in the UK). KS, LA and CA guided analyses, assisted with interpretation and access to historical literature (in SA), besides providing editorial input on multiple revisions of the manuscript.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Abbreviations *Cefas*, Centre for Environment Fisheries and Aquaculture Science; *DAFF*, Department of Agriculture, Forestry and Fisheries; *FAO*, Food and Agriculture Organisation; *FIS*, Freight, Insurance and Shipping; *ICES*, International Council for the Exploration of the Sea; *QGIS*, Quantum Geographic Information System; *SAEON*, South African Environmental Observation Network; *SANBI*, South African National Biodiversity Institute; *SS*, Single-screw Steamship; *UCT*, University of Cape Town; *UK*, United Kingdom; *USA*, United States of America; *WGS84*, World Geodetic System 1984

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