A global review of catch efficiencies of towed fishing gears targeting scallops

Adam J. Delargy[a*], Lynda Blackadder[b], Isobel Bloor[c], Carrie McMinn[d], David B. Rudders[e], Claire L. Szostek[c], Helen Dobby[b], Mervi Kangas[f], Bryce D. Stewart[g], James R. Williams[h], Kevin D.E. Stokesbury[a]

[a]School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, USA; [b]Fisheries Advice Group, Marine Scotland Science, Aberdeen, United Kingdom; [c]School of Ocean Sciences, Bangor University, Bangor, United Kingdom; [d]Environment and Marine Sciences Division, Agri-Food and Biosciences Institute, Belfast, UK; [e]Virginia Institute of Marine Science, William and Mary, Gloucester Point, USA. [f]Aquatic Science and Assessment, Department of Primary Industries and Regional Development (DPIRD), Hillarys, Australia; [g] Department of Environment and Geography, University of York, York, UK; [h]National Institute of Water & Atmospheric Research Ltd (NIWA), Auckland, New Zealand.

ORCID ID

Adam J. Delargy: https://orcid.org/0000-0003-0187-1310

Lynda Blackadder: https://orcid.org/0000-0001-7909-4174

Carrie McMinn: https://orcid.org/0000-0002-7112-951X

David B. Rudders: https://orcid.org/0000-0001-5571-0817

Claire L. Szostek : https://orcid.org/0000-0002-0122-1070

Mervi Kangas: https://orcid.org/0000-0002-4387-2277

Bryce D. Stewart: https://orcid.org/0000-0001-5103-5041

* adelargy@umassd.edu

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Abstract

The catch efficiency of towed fishing gears is the fraction of the target species in the gear path that were caught and retained. Catch efficiency is fundamental for calculating population status required for establishing fisheries management reference points. Consequently, catch efficiency has been estimated for many commercially important scallop (Pectinid) fisheries. This article synthesizes and discusses estimates of catch efficiency of towed gears used to target scallops, the methods for estimating catch efficiency and the factors that influence these estimates. There exists considerable variation in catch efficiency estimates among studies (0.1 to 0.7), and it is important that this variation is accounted for during surveys and stock assessments to avoid erroneous advice and estimates. The high variation was driven by differences in experimental conditions, estimation methods and scallop behavior. Scallop size and substrate type were the two most common reporting categories discussed in the studies and consequently should be considered the two most important drivers of catch efficiency. Other important factors such as gear specifications, and scallop species were featured in some studies. This review will be highly useful for designing catch efficiency experiments, survey design and stock assessments by understanding, and accounting for, catch efficiency variation.

Keywords: scallops, catch efficiency, gear design, global review, survey design.

Introduction

The efficiency of a towed fishing gear to catch the target species is an important consideration of commercial fishing operations, scientific surveys, and assessments of natural finfish and shellfish populations. Commercial fishing operations generally focus on maximizing profits and are therefore likely to seek high catch efficiency, whilst balancing other considerations such as fuel efficiency and bycatch legislation (Shepperson et al. 2016). In contrast, fishery-independent surveys focus on consistency and standardization of catch efficiency so that changes in target species abundance or biomass over space and time may be detected (Pennino et al. 2016). Therefore, the catch efficiency of commercial fishing operations and fishery-independent surveys are of high interest to fishers, fishery scientists and managers.

Understanding the impact of commercial fishing operations on exploited finfish or shellfish populations is a key component of sustainable management (Butterworth et al. 2014; Cadrin et al. 2016). In this context, catch efficiency represents the link between the amount of fishing effort expended and the target species returns. Fishing gear regulations are a key driver of the catch efficiency of commercial fishing, which determines how effectively fishing operations can remove target species and bycatch (Catchpole and Gray 2010). Changing catch efficiency can affect the probability of capture and therefore affect fishing mortality (Kennelly 2007; Cadrin et al. 2016). Catch efficiency often varies with target species size, often lowering the capture probability of small, immature individuals that allows more to reach maturity and contribute to the population through reproduction (Gabriel et al. 1989; Caddy and Seijo 2002), while at the same time maximizing yield per individual captured. Changes to fishing mortality and recruitment driven by fishing operations and their efficiency can have profound effects on stock sustainability (Butterworth et al. 2014).

Catch efficiency is also an important consideration of fishery-independent surveys, which are designed to provide unbiased samples of finfish or shellfish populations. These samples are often used in stock assessments, which are quantitative techniques to estimate the status of fish or shellfish populations (Hilborn and Walters 1992; Somerton et al. 1999; Cadrin et al. 2016). Consistency and reduction of bias in fishery-independent surveys is crucial to enable detection of changes to indices and stock status over time and space (Pennino et al. 2016). Fishery-dependent catch rates can also be used in stock assessments and knowledge of differences in catch efficiency improves the standardization of these data to better capture trends in stock status (Lordan et al. 2011). Stock assessment outputs can be highly sensitive to catch efficiency estimates and assumptions, but their outputs are often used directly by management (Cadrin et al. 2016). Using incorrect measures of catch efficiency can result in estimated changes in population size that differ from reality. Understanding and quantifying catch efficiency can help reduce uncertainty in stock assessments and resultant estimates of population sizes (Cadrin et al. 2016; Miller et al. 2019).

Scallops (Pectinidae) are a family of marine bivalves containing around 400 known species and are found in all seas of the world with a number contributing to commercial fisheries (Brand 2016). Global landings of scallops have increased considerably in recent decades (Stewart and Howarth 2016). Due to increasing commercial significance, fishery-independent surveys are commonly implemented for many scallop stocks and the data used in stock assessments (e.g., Nasmith et al. 2016; Dobby et al. 2017; NEFSC 2018). Several scallop species also have catch efficiency estimates and are the constituents of fisheries on continental shelves (Table 1) (Brand 2016). Many scallop surveys use towed fishing gears, and a wide variety of sampling location selections is employed, including returning to fixed stations (Bloor et al. 2017; Dobby et al. 2017; ICES 2018), systematic (Burt et al. 2021; Kangas et al. 2021), hybrid of systematic and random (Delargy et al.

2019) and stratified random (Dichmont et al. 2000; Harrington et al. 2007; NEFSC 2014; Williams et al. 2014; Nasmith et al. 2016; ICES 2018). When present, stratification is typically based on catch rates from previous years in these surveys but can be based on depth and latitude.

In addition to quantifying catch efficiency for stock assessments, studies have also focused on technological, environmental, and biological factors effecting changes in catch efficiency (Orensanz et al. 2016). The fisheries that have quantified catch efficiency tend to use either dredges or trawls (Table 1), but a wide range of specifications of these gear types exist to account for local conditions and the recessing and swimming abilities of each scallop species.

Several of the commercially important scallop species recess into the seabed so that the upper shell is level with or slightly under the seabed (Brand 2016). The degree of recession varies, for example king scallops (*Pecten maximus*) typically recess deeper than queen (*Aequipecten opercularis*) or sea (*Placopecten magellanicus*) scallops, which lie on top of the seabed (Brand 2016). The degree of recession is important for catch efficiency as gears that can penetrate the seabed are required for those species that deeply recess.

A further key feature of scallops is their ability to swim by jet propulsion as an escape response (Joll 1989; Brand 2016; Guderley and Tremblay 2016). Swimming ability varies across species, by season (Jenkins et al. 2003), and by individual size within species (Fifas et al. 2004; Brand 2016). Swimming ability typically increases with body size; however, the swimming range of king and sea scallops eventually decreases at very large body sizes (Caddy 1968; Minchin and Mathers 1982; Stokesbury and Himmelman 1996). The strongest swimming commercial species are the queen, saucer (*Ylistrum* (formerly *Amusium*) *balloti*), and sea scallops (Brand 2016). Swimming ability affects catch efficiency as stronger swimming species or individuals have a greater chance of evading capture.

The aim of this article is to review the elements of catch efficiency of scallop towed fishing gears and then present and synthesize estimates that have been made. The review begins by defining absolute catch efficiency, reviewing factors affecting catch efficiency and highlighting methods used to estimate catch efficiency in fishery-independent field studies or from fishery-dependent catch data. The article then reviews all catch efficiency estimates of currently used scallop towed gears from peer-reviewed literature and discusses notable estimates from gray literature. Estimates are presented together by species, gear, size group and substrate type as much as possible, as these are the primary ways efficiency estimates were reported within individual studies. Estimates are also separated by whether they were estimated from a toothed gear or a non-toothed gear, as these gear classifications have different components affecting efficiency. Size-based catch efficiency curves are also reproduced and compared. In addition, key factors that may be driving differences in the catch efficiency estimates are discussed by considering both trends across studies and points of discussion raised by individual studies.

Catch efficiency, catchability, and selectivity

Catch efficiency, catchability and selectivity are terms used in fishery stock assessment literature that are easily confused (Cadrin et al. 2016). All three are important parts of the probability of capture of an individual of the target species. Catch efficiency and catchability are closely linked, and sometimes used interchangeably, but they are distinct. Absolute catch efficiency (k) is the fraction of the target species that are caught and retained by the gear compared to the number of scallops in the gear path (Caddy 1989; Walter et al. 2007; Miller et al. 2019) (Equation 1).

$$k = \frac{no.\, scallops\ caught}{no.\, in\ gear\ path} \qquad (Equation\ 1)$$

This metric is the focus of this review, and it is bounded by zero and one, or may be expressed as a percentage by multiplying Equation 1 by 100. Catch efficiency may be referred to as capture efficiency, as is often the case when discussing optical methods for estimating abundance (Stokesbury 2002; Bethoney and Stokesbury 2018). Importantly, absolute catch efficiency differs from relative catch efficiency, which is often used to compare different or modified gear types to each other (Millar and Fryer 1999). Relative catch efficiency is the fraction caught relative to another gear, rather than the fraction caught from the seabed. This review is restricted to absolute catch efficiency estimates, as relative efficiency estimates have limited meaning outside their respective field study (Millar and Fryer 1999; Orensanz et al. 2016), and therefore absolute catch efficiency is referred to as catch efficiency hereafter.

Catchability (q) is the fishing mortality rate (F) applied to an entire population by a unit of fishing effort (E) (Arreguin-Sanchez 1996; Cadrin et al. 2016) (Equation 2). This equation is also appropriate for fishery-independent surveys (Cadrin et al. 2016).

$$q = \frac{F}{E} \qquad (Equation\ 2)$$

As fishing mortality rate is a measure of relative catch, catchability can also be defined from the population size (N) over the period of the catches (C) (Cadrin et al. 2016) (Equation 3).

$$q = \frac{C}{EN} \qquad (Equation\ 3)$$

Catchability is linked to catch efficiency by the proportion of population area (A) which is exposed to the fishery or scientific experiment (a) (Dickie 1955; Walter et al. 2007; Cadrin et al. 2016) (Equation 4). This relationship between catchability and catch efficiency assumes uniform distribution of the population across the population area, which may not be realistic for scallop populations because they tend to aggregate in numerous dense beds within a fishing ground (Brand 2016). This is another reason why catch efficiency is the preferred focus of this review.

$$k = q\frac{A}{a} \qquad (Equation\ 4)$$

Selectivity (*s*) traditionally refers to the fraction of scallops caught from those entering the gear (Caddy 1989), however selectivity occurs at many more stages in the fishing process. Two broader components of selectivity are population selectivity and contact selectivity, where the former describes the proportion of scallops available to the fishery and the latter is the proportion of scallops caught and retained once exposed to the fishery (Maunder et al. 2014; Cadrin et al. 2016). Both types of selectivity vary with demographic structures of a scallop population, such as by age, length, maturity, or weight groups. Population selectivity is the proportion of each demographic group that is available to the fishery and is primarily determined by the spatial distribution of scallops within a fishery (Maunder et al. 2014). Fishers may avoid a section of the population based on sea conditions, depth, distance from port, local abundance, ground type, and marketing quality of the product (Orensanz et al. 2016; Shepperson et al. 2016; Rudders et al. 2019a). Groups of scallops of similar age (cohorts) or length may be represented in greater proportion in particular regions based on where they settled (Brand 2016), and therefore areas within a fishery will have differing population selectivity (Orensanz et al. 2016).

Contact selectivity for scallops is affected by the ability of scallops to avoid entering the towed gear if in the towpath, the ability of the towed gear to capture scallops in its path and the retention of scallops that have entered the gear (Orensanz et al. 2016). Scallops can avoid towed gears by swimming to the side, under or over the mouth of the gear opening, and the ability to do this varies by size, age, condition, season, and species (Jenkins et al. 2003; Brand 2016; Orensanz et al. 2016). The gear may be unable to capture scallops if they are between rocks, lodged in the sediment, pass underneath the gear or because the gear bounces over seabed features, and this process usually favors smaller scallops avoiding capture (Fifas and Berthou 1999). The ability to retain scallops after they have entered the gear is generally size dependent and controlled by dredge ring and net mesh diameters (Courtney et al. 2008; Chandrapavan et al. 2012) but is often also controlled by factors such as the amount of debris in the gear (Caddy 1989; Orensanz et al. 2016).

The catch efficiency values for scallop towed gears incorporate a wide range, including groups below and above a minimum landing size (MLS), within a defined size range and demographic group curves. The most common of the latter are size-structured catch efficiency curves (Orensanz et al. 2016).

Gear design and catch efficiency

Although scallops are caught by divers in some fisheries, and considerable amounts are grown in aquaculture in other areas, the most common method of harvesting wild scallops is using towed fishing gears (Stewart and Howarth 2016) (Table 1). The choice of gear depends on a combination of the mobility of the species, the ability of the species to recess and the type of substrate in the fishery (Stewart and Howarth 2016). Species that are more mobile, such as the queen or saucer scallop, can be harvested using otter trawls, whereas more recessing, sedentary species, such as the king scallop and Australian (*Pecten fumatus*) scallop, require dredges designed to contact or penetrate the seabed (Brand 2016; Orensanz et al. 2016). The wide variety of scallop species and substrates around the world have resulted in a range of dredge or trawl designs and each design, mesh net size and gear configuration results in differing catch efficiencies (Figure 1) (Orensanz et al. 2016; Stewart and Howarth 2016).

Dredges have a variety of forms that span rigid framed structures to modified beam trawls (Orensanz et al. 2016). Rigid frame dredges may have teeth, and these may be fixed or spring-loaded, and the dredge may resemble a cage or a chainmail bag (Orensanz et al. 2016; Stewart and Howarth 2016). Teeth are metal prongs on the bottom of the dredge used to dislodge scallops from the sediment. Dredges that resemble beam trawls likely have a lower sweep chain and more rigid supports than standard beam trawls (Orensanz et al. 2016). The Rapido gear used to target Mediterranean (*Pecten jacobaeus*) and queen scallops in the Mediterranean Sea is an example of a modified beam trawl (Hall-Spencer et al. 1999). The width of individual dredges can also vary considerably, with some North American dredges 4.57 m wide and some European dredges only 0.61 m wide (Duncan et al. 2016; Stewart and Howarth 2016).

The key aspects of dredge design that affects catch efficiency (if present) are the spring compression, the mouth width, the belly rings, and the net mesh (Fifas et al. 2004). French plate dredges and New Zealand box dredges also have a diving plate that can influence catch efficiency (Beentjes and Baird 2004; Fifas et al. 2004). The belly ring and net mesh diameters are highly important for catch efficiency and control the fraction of scallops that are retained in the dredge once caught (Chapman et al. 1977; Beukers-Stewart et al. 2001; Lart et al. 2003). Many other properties of dredges can affect catch efficiency including the weight, shoes, wheel size, dimensions of the tow bar and type and length of warp used to tow the dredges.

The teeth on toothed dredges are also a key component of catch efficiency. The length and number of teeth affect the ability of the dredges to dislodge scallops from the seabed and determines the gap between the bottom of the dredge and the seabed (Mason et al. 1979; McLoughlin et al. 1991; Fifas et al. 2004). This gap, combined with the spacing between the teeth, is important as scallops can evade capture by passing through these spaces (Chapman et al. 1977; Beukers-Stewart et al. 2001; Lart et al. 2003). Catch efficiency on toothless dredges is affected by the number of drag chains and the angle of the cutting bar. Scallops can escape under the drag chains, and this process tends to favor larger scallops avoiding capture (Caddy 1968). The mouth width, net mesh diameter and head rope length are key properties of otter trawls that effect catch efficiency (Fraser et al. 2007).

Factors affecting catch efficiency

In addition to variation between gear types, catch efficiency can be affected by a wide range of other factors. Fishing practices, gear configuration and environmental factors such as seabed substrate type, sea state and weather conditions directly affect the performance of the gear and hence catch efficiency, while conditions that influence the behavior of scallops can affect catch efficiency indirectly through altering their susceptibility to capture, or ability to escape the dredge.

Substrate type

Substrate type has a considerable influence on the catch efficiency of towed scallop gears (Caddy 1968; Fifas and Berthou, 1999; Beukers-Stewart et al. 2001). Higher efficiencies tend to occur on fine, soft substrates (smooth) and lowest efficiencies on rocky substrates (rough) (Dare et al. 1993; Currie and Parry 1999; Miller et al. 2019). Coarse sand or gravel tend to be the preferred substrate for many scallop species, and these often have intermediate catch efficiencies compared to smoother and rougher grounds (Dare et al. 1993; Currie and Parry 1999; ICES 2016). Fishing gear can be adjusted or modified to attempt to mitigate inefficiencies on rougher grounds including the use of rock chains on New Bedford dredges and reducing the tension in spring-loaded dredges to allow for greater give (Smolowitz et al. 1985; Boulcott et al. 2014).

Substrate type primarily influences catch efficiency through physical effects on components of the gear, however substrate type can also influence catch efficiency through indirect effects such as the ability of scallops to see, swim and recess into the seabed. In addition, catch efficiency is also affected when substrates support other organisms and the gear bag or net will fill faster, or the mouth of the gear may become blocked (Bourne 1965; Dare et al. 1993; Zhang et al. 1993). In otter trawl fisheries, this may be mitigated by the installation of bycatch reduction devices such as rigid or soft grids that facilitate exclusion of larger animals or debris whilst still retaining scallops

(Broadhurst et al. 2002; Kangas and Thomson 2004) Some substrate types and areas (e.g. newly opened rotationally closed areas) can have particularly high scallop densities and can reduce catch efficiency by blocking the mouth opening of the gear or filling the dredges too quickly, or increase catch efficiency by clogging the rings or net mesh so that smaller scallops are retained instead of being able to escape (Yochum and DuPaul 2008; Roman and Rudders 2019). Therefore, the effect of substrate type on catch efficiency also interacts with haul length and there can be density dependent effects.

Further environmental factors

Several environmental factors affect absolute catch efficiency in addition to the substrate type. The tidal strength and direction and sea state can affect the contact time of the gear with the seabed and the mouth opening, and therefore affect catch efficiency (Beukers-Stewart et al. 2001; Fifas et al. 2004). When there are high waves or swell the gear is more likely to bounce, and this reduces contact with the seabed (Lart et al. 2003). Water depth is an important environmental variable because it affects the ability of the gear to maintain towing traction as the pressure exerts force on the warp, which can result in reduced ability to maintain the gear in the desired position on the seabed and therefore reduce catch efficiency (Fifas et al. 2004; Orensanz et al. 2016). Weather conditions are also linked to seasons. For example, catch rates in the Asian moon scallop (*Amusium pleuronectes*) fishery in the Philippines are highest between April and June, which corresponds with the calmest sea states of the year (Del Norte 1988).

Environmental factors can further influence catch efficiency if they affect the swimming behavior of scallops, as greater swimming ability allows scallops to evade capture. The relationship between water current speed and scallop swimming is unclear, with some studies reporting increases in swimming activity in higher water current speeds (Gruffydd 1976; Stokesbury and Himmelman 1996) and other studies reporting less swimming or no change (Thorburn and Gruffydd 1979; Vahl and Clausen 1980). Daylight or water clarity can also affect scallop swimming, as scallop eyes can detect movements and changes in light intensity (Land 1966; Orensanz et al. 2016). This is a driver of the higher catch rates of saucer scallops during the night in Western Australia (Kangas et al. 2011).

Numerous studies have demonstrated patterns that indicate that the swim response of a range of scallop species is higher at higher sea temperatures (Ordzie and Garofalo 1980; Pitcher and Butler 1987; Manuel and Dadswell 1991; Parsons and Dadswell 1992; Jenkins et al. 2003). There are also many other factors affecting the swim response, such as reproductive stage, food availability, photoperiod, and energy reserves, and therefore it is often difficult to be certain about the drivers (Brand 2016; Guderley and Tremblay 2016). For example, the queen scallop swim response is affected by a combination of sea temperature, visibility, and fatigue (Jenkins and Brand 2001; Jenkins et al. 2003). The effect of higher sea temperatures on catch efficiency, via the swim response, may become more pronounced due to climate change, and therefore this is a key area for future catch efficiency research.

Fishing practices and vessels

The way a vessel fishes also affects catch efficiency. The haul speed, length, and direction relative to the tide, gear configuration and gear maintenance can each influence catch efficiency (Dare et al. 1993; Beukers-Stewart et al. 2001; Orensanz et al. 2016). Haul duration or length is highly important for avoiding clogging, and excessive haul duration can result in a reduction in catch efficiency (Engas and Godø 1989; Fifas et al. 2004; Fraser et al. 2007). Haul speed and the amount of warp used to tow the gear is important for maintaining contact of the towed gear with the seafloor, which is essential for sustaining catch efficiency (Carrothers 1981; Fifas et al. 2004; Reiss et al. 2006). In addition, skipper and crew skill can play a considerable role in catch efficiency and fishers tend to target areas of highest densities (Carrothers 1981; Szostek et al. 2017).

Vessel characteristics such as length, weight, engine capacity and number of dredges towed, affect catch efficiency (Byrne et al. 1981; Thorson and Ward 2014; Orensanz et al. 2016). Vessels used for dredging scallops can range from < 10 m in length on inshore grounds, to large factory vessels used in the offshore US/Canadian fishery that are over 40 m long. Larger vessels are more efficient, likely, because they roll and pitch less than smaller vessels, which will result in the dredges maintaining contact with the seabed for longer (Byrne et al. 1981; Basch et al. 2002). The engine capacity of a vessel will determine the ability to maintain the desired vessel speed in strong tides, and vessel speed affects catch efficiency (Fifas et al. 2004; Thorson and Ward 2014; Orensanz et al. 2016).

Physiological state

The physiological state of scallops is important for determining their ability to swim to avoid capture from towed gears. Catch efficiency is higher after areas have been repeatedly fished in some fisheries, and this is perhaps because scallops become fatigued (Olsen 1955; Jenkins and Brand 2001; Brand 2016), however the effect on catch efficiency may only be evident after several hauls have been conducted in an area (Guderley and Tremblay 2016). This effect of catch efficiency potentially being higher after repeated fishing may also be caused by gears reducing seabed topography leading to more consistent contact of the gear in later hauls (Currie and Parry 1999). Likewise, with recessing species, such as the king scallop, dislodging (but not capturing) scallops with the first pass of a dredge may increase the catch efficiency of subsequent tows (Beukers-Stewart et al. 2001). The reproductive cycle of scallops also affects their physiological state and their ability to swim, with reduced swimming activity demonstrated for several species after spawning events (Brokordt et al. 2000a; 2000b; 2006; Kraffe et al. 2008; Guderley and Tremblay 2016). Exposure to toxins and shell-fouling epifauna can each also reduce swimming activity (Chapman et al. 1979; Winter and Hamilton 1985; Donovan et al. 2002; 2003; Dijkstra and Nolan 2011; Brand 2016).

Scallop size also affects their physiological state and ability to swim, as swimming distance increases with body size (Fifas et al. 2004; Brand 2016), however lowered swimming ability may occur at largest sizes in king and sea scallops (Caddy 1968; Minchin and Mathers 1982; Stokesbury and Himmelman 1996).

Methods for estimating catch efficiency

A wide range of direct or indirect methods have been used to estimate the catch efficiency of towed gears targeting scallops. Direct methods are those that determine the abundance of scallops on the seafloor before or after fishing, typically using divers, optical technologies, or seed-recapture (Beukers-Stewart et al. 2001). Indirect methods infer catch efficiency from catch rates without knowing the scallop abundance on the seafloor and include depletion estimators, the index-removal method and hauls paired with a gear with known catch efficiency (catch ratio method).

Direct methods

Diver and optical sampling methods are used to quantify scallops within known areas of the seabed, for analysis with dredge catch data, to estimate catch efficiency of the gear. Optical technologies can include towed systems, autonomous underwater vehicles, and fixed camera systems (Howland et al. 2006; Singh et al. 2013; Walker et al. 2016; Bethoney and Stokesbury 2018; Miller et al. 2019; Semmens et al. 2020). Divers have been commonly used in catch efficiency studies for king scallop and New Zealand fisheries (Fifas and Berthou 1999; Beukers-

Stewart et al. 2001; Jenkins et al. 2001; Handley et al. 2004; Tuck et al. 2018). Optical methods have been used extensively in the sea scallop fishery (Caddy 1971; NEFSC 2010; Miller et al. 2019). Both these methods often assume 100% efficiency and can detect all scallops on the seafloor in the gear path (Beukers-Stewart et al. 2001; Miller et al. 2019; Rudders et al. 2019b). Experimental work on diver samples suggests they are 99% efficient at detecting scallops in New Zealand (Tuck et al. 2018). The two techniques have two variants that are straightforward to understand, either quantify the abundance of the seafloor before or after dredging. It is also possible to not sample the exact haul path and instead conduct adjacent diver or optical sampling, by assuming similar micro distributions of scallops (Tuck et al. 2018). These direct methods do not have to involve detailed mathematical approaches used in indirect methods for estimating catch efficiency, although mathematical modelling can be used in these approaches (Tuck and Brown 2008; Bian et al. 2012). Another benefit of direct observations is that there can be greater certainty over the exact gear position (Miller et al. 2019; Rudders et al. 2019b).

Both divers and optical methods are not without limitations and are often restricted to sampling smaller areas and may be confined to shallower waters than indirect methods (Beukers-Stewart et al. 2001). These visual sampling techniques may also suffer from violations of 100% detection efficiency, which can occur in poor visibility conditions, in complex habitats (e.g., substrates containing dead shells) or when targeting scallop species that recess and cover themselves with a fine layer of substrate. In addition, violations of 100% efficiency may incur a size effect, where detection probability is lower for smaller scallops (Jacobson et al. 2010).

An alternative direct method is placing a known quantity of scallops in areas of seabed with no natural scallop population, and this technique is referred to as a seed-recapture experiment. This technique has been implemented in multiple scallop catch efficiency studies (Dickie 1955;

McLoughlin et al. 1991; Dare et al. 1993). After seeding, scallops are typically given a few days to adjust to the substrate before being fished, and the catch efficiency can be straightforwardly obtained (Dickie 1955; McLoughlin et al. 1991; Dare et al. 1993). The simple calculation required for this technique is offset by challenges in the experimental design, such as finding an area that is suitable scallop habitat yet is not already populated. Once the area is established it may be challenging to strictly define the perimeter and ensure scallops have not moved out (Dickie et al. 1955; Rolfe 1969; Caddy 1971). These obstacles can be addressed using buoys, geo-positioning devices and by fishing around the defined perimeter to check for overspill (Dickie 1955; Rolfe 1969; Courtney et al. 2022).

Indirect methods

Indirect methods do not rely on knowledge of scallop abundance and instead estimate catch efficiency from changes in catch rates. These methods tend to require high levels of fishing effort, and the analyses can involve more complicated calculations or statistical modelling, however they can be conducted at the spatial extent of the fishery and are not restricted to shallow waters (Beukers-Stewart et al. 2001).

The most practiced indirect technique for estimating catch efficiency is depletion estimation, and this has been used in a wide range of scallop fisheries (Beukers-Stewart et al. 2001; Kangas and Morrison 2013; Delargy et al. 2022). Depletion estimation involves repeatedly fishing an area of seabed and the catch efficiency can be derived from the effect of removals on the consequent catch rates (Hilborn and Walters 1992). Leslie and Davis (1939) developed the first depletion estimator and showed that the relationship between cumulative catch and the catch per unit effort was linear, and that the x-intercept equaled the initial population size, and the negative of the slope was the catchability (Hilborn and Walters 1992; Walter et al. 2007). The catch efficiency can then be derived from the catchability and the ratio of the swept area to the study area (Lasta and Iribarne 1997; Gedamke et al. 2004; Walter et al. 2007). Like the Leslie-Davis (1939) method, the DeLury (1947) depletion estimator is based on declines in catch rate with cumulative fishing effort linearized by plotting the natural logarithm of catch per unit effort (CPUE) against cumulative effort (Ricker 1975; Gunderson 1993). Several studies have applied the Leslie-Davis or DeLury methods to scallop gears (Rolfe 1969; Joll and Penn 1990; Iribarne et al. 1991; Lasta and Iribarne 1997; NEFSC 1999; 2001; Beukers-Stewart et al. 2001; Gedamke et al. 2004; Walter et al. 2007; Kangas et al. 2011; Kangas and Morrison 2013; ICES 2016).

These linear depletion estimators assume that a large fraction of the population is removed, that the probability of an animal being caught is constant through the duration of the experiment, that all individuals have the same probability of being caught and that the population is closed (Rago et al. 2006). It can be challenging to ensure a closed population, and depletion experiments are often conducted over short periods to mitigate the impact of movement of individuals into or out of the area (Beukers-Stewart et al. 2001). This concern is lessened for those scallop species that have limited movements over time. In addition, linear depletion estimators assume that animal distribution is either uniform or random and that the uncaught population re-mixes after hauls (Rago et al. 2006; Hennen et al. 2012). Scallops typically violate these latter assumptions by aggregating in patches and having limited movement (Brand 2016). Modelling techniques using maximum likelihood have been used to address this issue, such as the Patch Model developed by Rago et al. (2006).

The Patch Model is spatially explicit and uses a record of the number of times positions on a fine scale grid have been fished during a depletion experiment (Wilberg et al. 2013). From this, the Patch Model predicts the CPUE from each haul for a given efficiency, and these can be compared to the observed CPUE from each haul. Maximum likelihood is used to estimate the catch efficiency given the CPUE observations. This approach relaxes the need for hauls to be conducted randomly throughout a depletion study and the model does not assume a linear decline in catches with greater number of hauls across the experiment (Rago et al. 2006). The model also does not assume animals re-mix during sampling, and instead assumes they remain in the same position throughout an experiment (Rago et al. 2006). The Patch Model has been used to estimate catch efficiency in a handful of scallop studies (NEFSC 1999; 2001; Delargy et al. 2022). Other extensions of linear depletion estimators into spatially explicit models have also been applied to scallop catch data (Gedamke et al. 2004; Walter et al. 2007).

The index-removal method is another indirect method, which estimates the catch efficiency from a fishing event using a pre-fishing survey index (I_1), a post-fishing survey index (I_2), the swept area of the surveys (*a*), the total fishing area (*A*) and the total catch from the fishing event (*C*) (Eq 5) (Gedamke et al. 2005; Hoenig and Pollock 2006).

$$k = \frac{\left(\frac{A}{a}\right)(I_1 - I_2)}{C} \tag{5}$$

This method has similar assumptions to linear depletion estimators, namely that the population is closed, and all individuals have the same probability of capture (Gedamke et al. 2005). In addition, the method assumes the two surveys have the same catch efficiency and that the sizes of the survey samples are negligible compared to the size of the catch (Gedamke et al. 2005). This method was applied to estimate the catch efficiency of New Bedford dredges targeting sea scallops during the 1998/1999 fishing season (Gedamke et al. 2005).

Some studies in North America have estimated catch efficiency for one gear using knowledge of catch efficiency from another gear and catch data from paired tows conducted between the two gears (Dickie 1955; NEFSC 2001; Miller et al. 2019). This is the catch ratio method, where k_2 is the known absolute catch efficiency of one gear, e_1 and e_2 are the relative efficiencies of each gear to each other and k_1 is the absolute catch efficiency of the gear to be estimated (Eq 6). This method is not possible without first having applied another method to estimate the catch efficiency of one of the gears.

$$k_1 = \frac{e_1}{e_2} k_2 \tag{6}$$

Comparison of methods

There have been few studies that have conducted two (or more) catch efficiency estimation techniques to compare the estimation methods for scallop gears. Rolfe (1969) found that depletion estimation produced a higher catch efficiency estimate (0.332) for the now redundant Baird dredge targeting king scallops compared to a seed-recapture study (0.243). Rolfe (1969) consequently questioned the suitability of the DeLury depletion method for scallop populations. Beukers-Stewart et al. (2001) found that depletion estimation catch efficiency estimates were lower than those obtained by divers (0.243-0.295 compared to 0.380-0.401), when studying Newhaven spring-loaded dredges targeting king scallops. Beukers-Stewart et al. (2001) suggested that scallops had moved into the small depletion area, biasing the depletion estimates downwards, whilst divers not being able to detect all scallops may have biased the efficiency derived from this technique upwards. These two studies serve as examples of how catch efficiency estimates can depend on the estimation technique employed, and how each technique has different considerations.

Dickie (1955) estimated the catch efficiency of commercial Digby dredges targeting sea scallops by seed-recapture experiments and catch ratio experiments. The overlapping size classes (60-80 mm SH) between the techniques showed reasonable agreement with some overlap in catch efficiency (seed-recapture 0.004-0.021 compared to catch ratio 0.016-0.031) and Dickie (1955) combined the estimates from the two techniques to produce final estimates. Therefore, this study demonstrates that it is possible to obtain similar estimates of catch efficiency using different techniques.

Catch efficiency estimates from photograph surveys and depletion estimation were compared for both New Bedford commercial dredges (89 mm belly ring diameter) and scientific New Bedford dredges (51 mm belly ring diameter and 38 mm mesh liner) targeting sea scallops (NEFSC 2001). In one region, catch efficiency was highest from photograph estimates (0.84 compared to 0.38-0.64 from depletion) but the reverse was true in another region (0.32-0.34 compared to 0.45-0.90 from depletion). Therefore, estimate technique performance is likely to be related to local conditions, and it is recommended that multiple estimation techniques are used simultaneously to improve confidence in catch efficiency estimates (NEFSC 2001).

Estimates of catch efficiency

Estimates of catch efficiency of gears targeting scallops exist for a range of toothed and non-toothed gears, scallop species, demographic groups, estimation methods, experimental and natural conditions and from a mixture of fishery-independent experiments and estimates derived from commercial catch rates (Table 2; Table 3). The wide variation of these factors in individual studies makes direct comparison of catch efficiency challenging among studies and scallop fisheries. Catch efficiency estimates were estimated without consideration of scallop size or then for specific size groups and sometimes both, in individual studies. It was common for studies to provide separate estimates of catch efficiency for specific size groups or by substrate type, or by a combination of the two (aggregated in Table 2 and Table 3). In addition, some studies estimated size-based catch efficiency curves from their observations. The common presentation of catch efficiency results using these two factors highlight scallop size and substrate type are considered the two most important drivers of catch efficiency among researchers. In addition, some individual studies provided estimates for different estimation techniques (Dickie 1955; Beukers-Stewart et al. 2001; NEFSC 2001), gear types and variants of the same type of gear (Dickie 1955; Dupouy 1982; Giguere and Brulotte 1994; Cryer and Morrison 1997; Fifas et al. 2004; Malloy 2016; Miller et al. 2019), species (Hall-Spencer et al. 1999) and age groups (Buestel et al. 1985; Fifas 1993). Some of these individual studies permit comparisons of techniques or gear variants that are otherwise challenging among studies due to variation in other conditions.

Catch efficiency estimates not accounting for scallop size

Estimates that do not account for scallop size mostly fall between 0.l and 0.7 for all gears and species (Figure 2). Smooth habitat types (where studies used language such as smooth, sand, or gravel to describe the substrate) characterized the highest estimates. This is consistent with most individual studies that reported catch efficiency for specific habitats (Table 2; Table 3), with catch efficiency highest on smooth substrates and lowest on rougher ones (Buestel et al. 1985; Dare et al. 1993; Currie and Parry 1999; ICES 2016; Miller et al. 2019). Low catch efficiency estimates were also reported from smooth substrates likely due to the other wide ranging factors affecting scallops among studies (Figure 2).

Direct comparison of estimates between studies is challenging, however some studies have directly compared catch efficiency for different dredge types (not just variants of the same type) and scallop species under the same conditions. Dupouy (1982) showed St Brieuc dredges to be more efficient at targeting king scallops than French plate dredges (0.35 compared to 0.30). Cryer and Morrison (1997) showed that New Zealand box dredges were more efficient (0.24-0.90) than New Zealand ring-bag dredges (0.02-0.09) and Japanese dredges (0.05-0.20) targeting New Zealand scallops. The authors acknowledged that their results were biased towards the box dredges because all experiments were conducted on box dredge fishery grounds, for which the gear was optimized towards, and all gears were operated by a vessel and captain experienced with the box dredge. In addition, the study was likely negatively biased towards the Japanese dredge because this gear is not typically used to target New Zealand scallops unlike the other two gears used in the experiment. Hall-Spencer et al. (1999) provided the sole example of a study quantifying the catch efficiency of two scallop species using the same gear under the same conditions. This study demonstrated that the Rapido trawl is more efficient at catching Mediterranean scallops (0.44) than queen scallops (0.11). This large difference in catch efficiency highlights the important role of species behavior and physiology in catch efficiency.

Size based catch efficiency curves

Several studies have estimated size-based catch efficiency curves, by fitting mathematical models, or by drawing lines, to size-specific catch efficiency observations (Figure 3). Some of these studies have produced multiple curves to depict differences in size-based catch efficiency with substrate type, or gear variants. Catch efficiency was lowest for smaller scallop sizes in all curves, however the shape of the curves for medium to larger sized scallops differs with some dome-shaped, some s-shaped and others that do not fit either of these patterns. Most curves had highest efficiency at the largest scallop sizes studied, with several of these curves plateauing (Figure 3). The highest peak size-based efficiencies were observed in the New Zealand box dredges, and the lowest peak efficiencies observed in the Digby dredges. The dome-shape curves were characterized by highest efficiency occurring for medium sized scallops, and lower efficiency for larger scallops and this is case for the scientific French plate dredge with 75 mm tooth length and two of the Newhaven spring-loaded dredge curves, all of which target king scallops (Figure 3).

The three catch efficiency curves available for French plate dredges demonstrate the effect of gear design on size-specific catch efficiency, with the two scientific dredges more efficient at catching smaller scallops than the commercial dredge, which had a wider belly ring diameter (72 mm or greater compared to 50 mm) (Figure 3). Higher catch efficiency in finer belly rings is consistent with other scallop studies that have directly compared the catch efficiency of gears with different belly ring sizes under the same conditions (Dickie 1955; Giguere and Brulotte 1994; Miller et al. 2019). Similar catch efficiencies for gears with different belly ring diameters can be obtained by constraining efficiency estimates to scallop sizes that both gears fully select for (NEFSC 2001). The differences between the two French scientific dredge curves (both with 50 mm belly ring diameter) were driven by tooth size, with shorter teeth (75 mm compared to 90–130 mm) resulting in a dome-shaped catch efficiency curve. This observed decrease in catch efficiency in larger scallops was caused by larger scallops being able to bury deeper than the shorter teeth can penetrate and the ability of larger scallops to swim effectively to avoid the dredges (Fifas et al. 2004). In addition, shorter tooth length led to a smaller gap between dredge and the seafloor (Fifas et al. 2004).

The Newhaven spring-loaded dredge curves from gear with 1.22 m mouth width (Chapman et al. 1977) showed distinct differences by sediment type, with the rough, rocky substrate resulting in a dome-shaped curve and the smoother substrate showing a continual increase in catch efficiency with increasing scallop size. This dome-shaped effect may not be restricted to rough substrates as the response was also detected in a later study on smooth substrates focused on dredges with 0.75 m mouth width (Dare et al. 1993). On the rough substrate, Chapman et al. (1977) observed the tooth bars on the dredges pushing aside larger scallops and noted that larger scallops were deeper recessed into the seabed, which would help avoid capture. Stones blocking the entrance of the dredge to larger scallops may also cause this effect (Dare et al. 1993).

Catch efficiency estimates for size groups

In addition to size curves, many studies have reported scallop catch efficiency estimates for size groups (Figure 4). These are either scallops less than a particular size (often distinguishing recruits or those below an MLS), a size range with lower and upper bounds or scallops greater than a particular size (often distinguishing fully recruited scallops or those above an MLS). Catch efficiencies have been reported for many different size groups in the literature, reflecting individual study preferences and MLSs differing with time and space (Figure 4). Most low catch efficiencies (< 0.08) occurred in the less than a particular size groups, reflecting the selectivity of gears. Highest efficiencies tended to occur in the size groups with a lower limit, which is intuitive that excluding small scallops would result in greater catch efficiency. Several of the catch efficiencies for this type of size group are lower than may be expected and this may be consistent with the reduction in efficiency observed at large scallop sizes in the dome-shaped size catch efficiency curves (Figure 3). This effect is not possible to fully assess by comparing the size group catch efficiencies among studies due to the great variation in study conditions.

Catch efficiency derived from fishery-dependent sources

The four studies that have estimated catch efficiency from fishery-dependent catch data (Gedamke et al. 2004; 2005; Walter et al. 2007; Kangas et al. 2011) are a small number compared to those that have estimated efficiency from fishery-independent experiments. Two of these fishery-dependent studies have wide ranges of catch efficiency estimates, which may reflect that the underlying catch rates were obtained across a wide range of conditions (Walter et al. 2007; Kangas et al. 2011). The two studies that provided catch efficiency estimates averaged across scallop size for New Bedford commercial dredges with 89 mm wide belly rings were well within the range estimated by fishery-independent experiments conducted using the same commercial gear (0.20 – 0.55 compared to 0.06 – 0.82) (Gedamke et al. 2004; Walter et al. 2007). The range of catch efficiency estimates for otter trawls targeting saucer scallops from fishery-dependent sources was much wider than the two studies that made fishery-independent estimates of this same gear (0.179 – 0.691 compared to 0.496 – 0.644) (Joll and Penn 1990; Kangas et al. 2011; Kangas and Morrison 2013). Therefore, the fishery-dependent estimates were not higher than the fishery-independent estimates across these fisheries, as might be expected if assuming fishers are attempting to maximize catches. This is because fishery-independent experiments may also target high density areas to replicate commercial activities and to get sufficiently high catch rates.

Insights from individual studies

Many of the gear and species combinations reviewed here have had catch efficiency estimates made by several studies and, in some cases, spanning long time periods. Some of the estimates incorporated in this review have subsequently been superseded by more recent studies, and these can provide useful insight. For example, Currie and Parry (1999) produced catch efficiency estimates for mud dredges targeting Australian scallops that were considerably higher than catch efficiency estimates from an earlier study (McLoughlin et al. 1991). The earlier study was conducted on substrates comparable to the firm ground type in the later study, which resulted in the lowest catch efficiency estimates (Currie and Parry 1999). The key differences between the two studies were the limited number of hauls, considerably lower vessel speeds (2 to 3 kts in McLoughlin et al. (1991) compared to 5.5 to 6.5 kts) and the use of teeth on the dredges by McLoughlin et al. (1991) (Currie and Parry 1999).

Early catch efficiency estimates for scientific French plate dredges (Buestel et al. 1985; Fifas 1993) have also been considered problematic by later studies due to a low number of diver transects conducted to assess the efficiency, failure to account for size-at-age variation in age specific catch efficiency estimates and lack of consideration of substrate type in some cases (Fifas and Berthou 1999). Early catch efficiency estimates of scientific New Bedford dredges had relatively low efficiency estimates (Caddy 1971). Later studies have cited low hauling speeds (2 to 4 kts compared to the modern 4 to 5.5 kts) as the primary reason for these low efficiencies (Gedamke et al. 2004; Miller et al. 2019). These insights reinforce that a variety of factors can influence catch efficiency estimates. Interestingly, several of these studies cite towing speed as a reason for large differences in catch efficiency among studies and therefore this should be considered a high priority factor.

For New Zealand fisheries, only the most recent catch efficiency estimates are included in this review. This is because there have been numerous (gray literature, although subject to local peer-review processes) estimates made over long periods by a single organization, who consider their most recent estimates to have superseded previous estimates. Summaries of previous estimates are available in Beentjes and Baird (2004) and Williams et al. (2014). The initial size-based catch efficiency curve estimates for the ring-bag dredges had the highest values for the smallest scallop sizes (Tuck et al. 2008) and advances in curve fitting was made in a subsequent study focused on the box dredges, depicting dome-shaped catch efficiency (Bian et al. 2012). Whilst improved, the curves were suspected to have underestimated catch efficiency for scallops 85 mm (SW) or smaller and were overparameterized (Williams et al. 2014; NIWA 2021). The more recent estimated curves for both these dredge types are now s-shaped (Tuck et al. 2018; NIWA 2021).

Final discussion

Catch efficiencies of towed gears targeting scallop species vary considerably in and across most of the gear-species combinations reviewed. This high variation indicates the challenges for scientists to maintain constant catch efficiency during fishery-independent research and ensure survey indices are comparable across a variety of conditions when sampling natural scallop populations. The observed variation is driven by studies estimating catch efficiency over a wide range of environmental and technical conditions and potentially being influenced by estimation methodology. Scallop size and substrate type were the two most common factors examined when reporting catch efficiencies in individual studies, highlighting that these are two highly important drivers of catch efficiency. Gear design (primarily belly ring and net mesh diameter and tooth length), estimation method, towing speed, and scallop species, which require specific habitat types, were each demonstrated, or strongly suggested, to also be important factors. The estimates reviewed in this article varied over a wide range of most of these factors and fishery-independent scallop surveys are also likely to encounter a wide range of variation in these factors both within and among surveys.

Whilst it is beyond the scope of this article to review all catch efficiency estimates from non-scallop fisheries, the common range of scallop catch efficiencies (0.1 to 0.7) is in line with many other non-scallop fishery estimates (e.g., Lauth et al. 2004; Reiss et al. 2006; Somerton et al. 2007). Very high efficiencies are possible in some fisheries where gear design is highly specialized, such as trawl fisheries targeting flatfishes (e.g., Munro and Somerton 2002). Efforts to increase the efficiency of scallop gears are to be encouraged (with appropriate management), because damage and mortality of scallops and other animals that encounter dredges, but are not captured, can be significant (Jenkins et al. 2001).

The catch efficiency estimates for some of the reported scallop métiers are well understood, with strong agreement between studies (i.e., scientific dredges used in France to sample king scallops), whereas other categories have limited studies and are therefore an area for further research (i.e., gears targeting Mediterranean and queen scallops). Other categories, such as the gear variants of the New Bedford dredge used to target sea scallops, have numerous studies resulting in wide ranges of catch efficiency estimates. The review identified differences in amounts of peer-reviewed and gray literature studies that adds for further consideration when assessing catch efficiencies. These differences in quality and quantity of catch efficiency estimates further reinforces the high variability that exists among studies.

For many towed gear surveys targeting scallops, the gear design and target species will remain constant. It is also reasonably straightforward to standardize towing speed (Hilborn and Walters 1992). Therefore, scallop size and substrate type may be the most important factors to account for in towed gear fishery-independent surveys of scallop populations. The effect of scallop size on catch efficiency is reflected in numerous reviewed studies that have estimated size-based catch efficiency curves and those that have presented estimates for distinct size groups. Many other studies have reported catch efficiency whilst not accounting for scallop size or have estimated catch efficiency over a wide-ranging size group. Consequently, such non-size specific estimates will be dependent on the size distribution of scallops present on the seabed, which is also known to be highly variable (Beukers-Stewart et al. 2001). Furthermore, these estimates are likely to be poorer at accurately estimating abundance or biomass from survey indices (either directly or through stock assessment methods) compared to size-based efficiency curves, which contain more information. Smaller scallops, which typically have lower catch efficiency, will be underestimated by using a single catch efficiency value applied to all sizes. Whilst size groups can help mitigate this issue without estimating a full size-based efficiency curve, care must be taken to ensure the size groups do not span a wide range of scallop sizes to receive the greatest benefit. This can be problematic for fisheries where the true efficiency curve has a steep decline in efficiency around a particular size (Beukers-Stewart et al. 2001) and is true of many of the fisheries reviewed here.

Substrate variation is likely to occur in many scallop survey areas. Stratified sampling is a renowned survey technique for dealing with known different mean and variance in survey indices (driven by different catch efficiencies and differences in abundance) under criteria (Kimura and Somerton 2006), and surveys should consider stratification of survey areas by substrate. Effective stratification requires knowledge of the strata criteria, and this may involve substrate surveys being conducted in some survey areas where substrate type is unknown or poorly understood. Most scallop surveys that already use stratification have strata determined by a wide range of management factors and commercial catch history, however in some cases these correspond well with distinct habitat regions, which helps to ensure some of the variation caused by substrate type is controlled for (NEFSC 2014; Nasmith et al. 2016). Another example of attempting to control for variance in survey indices caused by substrate type is apparent in the Scottish scallop survey, and although it uses a fixed station survey design the original placement of the fixed stations was conducted by a stratification method based on substrate type (Dobby et al. 2017).

There was evidence from multiple studies that size-structured catch efficiency for king scallops may be dome-shaped in some cases, where the catch efficiency is low for small scallops, peaks at mid-ranged sized scallops and then decreases for the largest scallops (Chapman et al. 1977; Dare et al. 1993; Fifas et al. 2004). This has important implications for stock assessment models, where often the modeler must specify either logistic s-shaped or dome-shaped size-structured catch curves when trying to best capture the fishing or survey process (Weinberg et al. 2016). There remains debate about whether size-based catch efficiency is dome-shaped for Newhaven dredges targeting king scallops, as it has not been detected in all cases (Chapman et al. 1977; Dare et al. 1993; Beukers-Stewart et al. 2001). Large scallops are often in relatively low abundance on commercial scallop grounds (Beukers-Stewart et al. 2005), and therefore it is important that variation in uncertainty along different parts of a size-based catch efficiency curve is accounted for. The New Zealand box dredge size efficiency curves have reverted to s-shaped after previously being estimated as dome-shaped (Bian et al. 2012; NIWA 2021). Therefore, there is uncertainty about whether size-based catch efficiency is s- or dome-shaped for scallops in some fisheries.

This review has highlighted several important survey and stock assessment considerations after evaluating many catch efficiency studies for gears targeting scallop species. Catch efficiency is highly variable and this makes it challenging for scientists to maintain constant catch efficiency during fishery-independent surveys. To account for this, surveys should strongly consider stratification by substrate type as catch efficiency can be highly variable with changes in this factor. In addition, surveys may wish to consider adjusting gear to habitat by changing spring tension or warp length. Such adjustments would need to be consistent over time during monitoring programs. This is important insight for scallop fishery scientists and managers using stock assessment approaches that are dependent on catch efficiency estimates or using catch data that span a wide range of substrate types. It is highly important that stock assessment approaches carefully consider sources of variation in catch efficiency rather than assuming this metric remains constant. The subjects and values reported here can be used to guide future catch efficiency field studies and stock assessments, particularly through prior distributions. This work is also likely to be useful to other fisheries to highlight variability in catch efficiency estimates and offer insight on estimation methods and driving factors that will be broadly applicable.

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Tables

Table 1: The commercially important scallop species that have catch efficiency values reported in this review. Other commercially important scallop species are not included in this table. Table information adapted from Orensanz et al. (2016). US dollar values converted using exchange rates on 06/15/2022.

Scientific name	Common name(s)	Notable fisheries
Aequipecten opercularis	Queen scallop	Small trawl fisheries in the Faroe Islands, France, and the Irish Sea.
Aequipecten tehuelchus	Tehuelche scallop	Small scale dredge and dive fisheries in Argentina.
Ylistrum balloti	Saucer scallop	Small trawl fisheries in Queensland and western Australia.
Patinopecten yessoensis	Japanese scallop	Major aquaculture and sea ranching in China and Japan.
Pecten fumatus	Australian scallop	Largest dredge fisheries in southern Australia. Some dive fishing.
Pecten jacobaeus	Mediterranean scallop Pilgrim's scallop	Small dredge and trawl fisheries in Adriatic and Aegean Seas.
Pecten maximus	King scallop Great scallop Coquille St Jacques	Major dredge fisheries in UK and France. Smaller dive operations throughout. Scallops (all species) were the fourth most valuable UK fishery in 2020, with a first sale value of \$51.2m and king scallop was 93.1% of this value (MMO 2021).
Pecten novazelandiae	New Zealand scallop	Dredge fisheries known in the Northland and Coromandel scallop stocks (northern North Island) and the Southern 'Challenger' stock (northern South Island). Historic dredge fishery at the Chatham Islands. Notable recreational fisheries throughout.
Placopecten magellanicus	Sea scallop Giant scallop	Major dredge fisheries in Canada and the US. Scallops (all species) were the fourth most valuable fishery in each country in 2019, with a first sale value of \$131.2 million and \$572.0 million respectively (DFO 2021; NMFS 2021).
Zygochlamys patagonica	Patagonian scallop	Industrial trawl fisheries in Argentina.

Table 2: Catch efficiency estimates for scallops from toothed towed gears. Catch efficiencies are presented in the demographic groups and sediment types reported in the individual studies and the table combines information where possible. A '-' in the habitat column means the estimate was not for a specific habitat type.

Gear	**Gear description**	**Species**	**Demographic group**	**Habitat**	**Catch efficiency estimates**	**Methods**	**Depth range**	**References**
Mud or peninsula dredge	Mouth width from 3.12-4.2 m. Teeth 100 mm long and 60 mm apart. Mesh lining 70 by 45 mm grid. Depressor plate present in some variants.	Australian scallop (*Pecten fumatus*)	All sizes	-	0.116–0.660	Divers, seed-recapture and DeLury depletion	12–17 m	Gwyther and McShane 1985 Gwyther and Burgess 1986 McLoughlin et al. 1991 Currie and Parry 1999
			< 72 mm SH	-	0-0.08 (95% CIs 0-0.108)			
			> 72 mm SH	-	0.121-0.140 (95% CIs 0.064-0.189)			
			> 70 mm SH	Soft	0.512–0.559 ± 0.019			
			> 70 mm SH	Medium	0.450–0.495 ± 0.048			
			> 70 mm SH	Firm	0.379–0.439 ± 0.049			
Japanese dredge	Mouth width 2.6 m	Japanese scallop (*Patinopecten yessoensis*)	All sizes	-	0.400-0.600	Unknown	Unknown	Kosaka 2016
St Brieuc dredges	Teeth 100 mm apart. Belly ring 72 mm diameter, Mesh 35 mm.	King scallop (*Pecten maximus*)	60-70 mm SH	-	0.086	Seed recapture	Unknown	Dupouy 1982
			70-80 mm SH	-	0.079			
			80-90 mm SH	-	0.164			
			> 90 mm SH	-	0.300			
French plate dredges	Toothed dredge (teeth 100 mm apart and 90 to 130 mm long). Belly ring 72 mm diameter, Mesh 35-92 mm. Depressor plate present.	King scallop	60-70 mm SH	-	0.086	Seed recapture	Unknown	Dupouy 1982 Fifas et al. 2004
			70-80 mm SH	-	0.148			
			80-90 mm SH	-	0.249			
			> 90 mm SH	-	0.350			

Scientific French plate dredges	Mouth width 2 m. Teeth 75-130 mm long, 30 per dredge. Belly ring and mesh diameter 50 mm.	King scallop	All sizes	Smooth	0.670	Divers	Unknown	Buestel et al. 1985 Fifas 1993 Fifas and Berthou 1999 Fifas et al. 2004
			All sizes	Rough	0.300			
			Age 2	-	0.500–0.558			
			Aged ≥ 3	-	0.675			
			Size curves		Available			
Newhaven spring-loaded dredges	Mouth width 0.75-1.22 m. 8-12 teeth, 76-110 mm long, 70 to 97 mm apart. Belly ring 75-90 mm diameter. Mesh 80-90 mm diameter.	King scallop	All sizes	-	0.134–0.227	Divers, seed recapture, Leslie-Davis depletion, towed camera system, Patch Model depletion	17–75 m	Chapman et al. 1977 Mason et al. 1979 Dare et al. 1993 Beukers-Stewart et al. 2001 Jenkins et al. 2001 Lambert et al. 2014 ICES 2016 Delargy et al. 2022
			< 80 mm SW	-	0-0.02			
			< 90 mm SW	-	0.030			
			80–89 mm SH	Smooth	0.269			
			80–89 mm SH	Non-smooth	0.163–0.241			
			90–109 mm SW	-	0.243–0.380			
			≥ 80 mm SW	-	0.142-0.162			
			> 90 mm SW	Smooth	0.406–0.580			
			> 90 mm SW	Sand	0.246			
			> 90 mm SW	Gravel	0.194			
			> 90 mm SW	Cobble	0.430			
			> 90 mm SW	Partly stony	0.290–0.330			
			> 90 mm SW	Stony	0.062–0.110			
			> 109 mm SW	-	0.260–0.620			
			Size curves	-	Available			
Scientific Newhaven spring-loaded dredges	Mouth width 0.76 m. Ten teeth 60 mm long. Belly ring and mesh 60 mm diameter.	King scallop	All sizes	-	0.290	Towed camera system	20–60 m	Lambert et al. 2014

Rapido trawl	Mouth width 3 m. 32 teeth 20 mm long spaced 78 mm apart. Net mesh 80 mm diameter.	Mediterranean scallop (*Pecten jacobaeus*)	All sizes	-	0.440	Towed camera system.	25 m	Hall-Spencer et al. 1999
		Queen scallop (*Aequipecten opercularis*)			0.110			
Box dredge	Mouth width 2 m.	New Zealand scallop (*Pecten novazelandiae*)	Size curves	-	Available	Divers	Various	NIWA 2021
Japanese dredge	Unspecified	New Zealand scallop	< 80 mm SW	-	0.022-0.040	Divers and catch ratio.	15-22 m	Cryer and Morrison 1997
			80-94 mm SW	-	0.059-0.073			
			≥ 95 mm SW	-	0.113-0.124			
Argentina dredge	Unknown	Tehuelche scallop (*Aequipecten tehuelchus*)	All sizes	-	0.150-0.210	Depletion	Unknown	Iribarne et al. 1991
Scientific Digby dredge	Mouth width 0.76 m. Teeth 60 mm long and 60 mm apart. Belly ring diameter 26 mm.	Sea scallop (*Plactopecten magellanicus*)	≤ 85 mm SH	-	0.150–0.780	Towed camera system	24–28 m	Giguere and Brulotte 1994
			> 85 mm SH	-	0.080–0.190			
			All sizes	-	0.060–0.820			

Table 3: Catch efficiency estimates for scallops from toothless towed gears. Catch efficiencies are presented in the demographic groups and sediment types reported in the individual studies and the table combines information where possible. A '-' in the habitat column means the estimate was not for a specific habitat type.

Gear	**Gear description**	**Species**	**Demographic group**	**Habitat**	**Catch efficiency estimates**	**Methods**	**Depth range**	**References**
Ring-bag	Mouth width 2.4 m.	New Zealand scallop (*Pecten novazelandiae*)	Size curves	-	Available	Divers	14-28 m	Tuck et al. 2018
Otter trawl	Gear length 13 m. Otter boards 1 m by 3.4 m, weighing 490 kg. Warp 26 m long. Head rope 15 m long. Mesh diameter 10 cm and cod-end mesh size 10 mm.	Patagonian scallop (*Zygochlamys patagonica*)	All sizes	-	0.210-0.310	Depletion estimators	90-105 m	Lasta and Iribarne 1997
Otter trawl	Mouth width 6.6 m. Wing mesh 50 mm diameter. Cod end mesh 45 mm diameter. Head rope 11 m.	Saucer scallop (*Ylistrium balloti*)	All sizes	-	0.179-0.691	Depletion estimators	16–40 m	Joll and Penn 1990 Kangas et al. 2011 Kangas and Morrison 2013
Digby dredge	Mouth width 5.49 m. Mesh diameter 66.7 mm	Sea scallop (*Placopecten magellanicus*)	All sizes Size curves	- -	0.120–0.690 Available	Seed recapture and catch ratio method	73 m	Dickie 1955
		Sea scallop	All sizes	Fine	0.640		Various	NEFSC 1999

New Bedford (89 mm belly rings)	Mouth width 4.6 m. Belly ring 88.9 mm. Twine tops 254 mm.		All sizes	Coarse	0.390	Depletion estimators, Index removal, towed camera system, catch ratio.		NEFSC 2001 Gedamke et al. 2004 NEFSC 2004 Gedamke et al. 2005 Walter et al. 2007 Miller et al. 2019
			≥ 80 mm SH	-	0.408-0.544			
			≥ 90 mm SH	-	0.320–0.840			
			All sizes	-	0.200-0.600			
New Bedford (102 mm belly rings)	Mouth width 4.6 m. Belly ring 102 mm. Twine tops 254 mm.	Sea scallop	All sizes	Fine	0.710	AUV camera system, catch ratio.	20-55 m	Yochum and DuPaul 2008 Walker 2013 Miller et al. 2019
			All sizes	Coarse	0.430			
			All sizes	-	0.021–0.630			
Scientific New Bedford	Mouth width 2.44 m. Belly ring 51-75 mm diameter. Mesh liner 38–44 mm diameter. Twine tops 89-144 mm.	Sea scallop	All sizes	Sand	0.400-0.440	Divers, various camera systems, catch ratio.	20–94.9 m	Caddy 1971 NEFSC 2001 NEFSC 2004 NEFSC 2007 NEFSC 2010 Malloy 2016 Miller et al. 2019 Rudders et al. 2019b
			All sizes	Coarse	0.270-0.380			
			"Juveniles"	-	0.194			
			< 50 mm SH	-	0.007–0.096			
			50–70 mm	-	0.360			
			50–75 mm SH	-	0.014			
			50–100 mm SH	-	0.203			
			75–100 mm SH	-	0.083			
			≥ 40 mm SH	-	0.365			
			≥ 45 mm SH	-	0.380–0.430			
			≥ 70 mm SH	-	0.360			
			≥ 72mm SH	-	0.318			
			≥ 85 mm SH	-	0.324 - 0.443			
			≥ 90 mm SH	-	0.320 – 0.840			
			> 100 mm SH	-	0.169			

Figure captions

Figure 1: Photographs of four different dredge types used to target scallops. Top left: New Bedford dredge, credit Deirdre Boelke. Top right: Newhaven spring-loaded dredges, credit Bryce Stewart. Bottom left: Australian 'mud' dredge, credit Jason Harrington. Bottom right: French plate dredges, credit IFREMER/Eric Foucher.

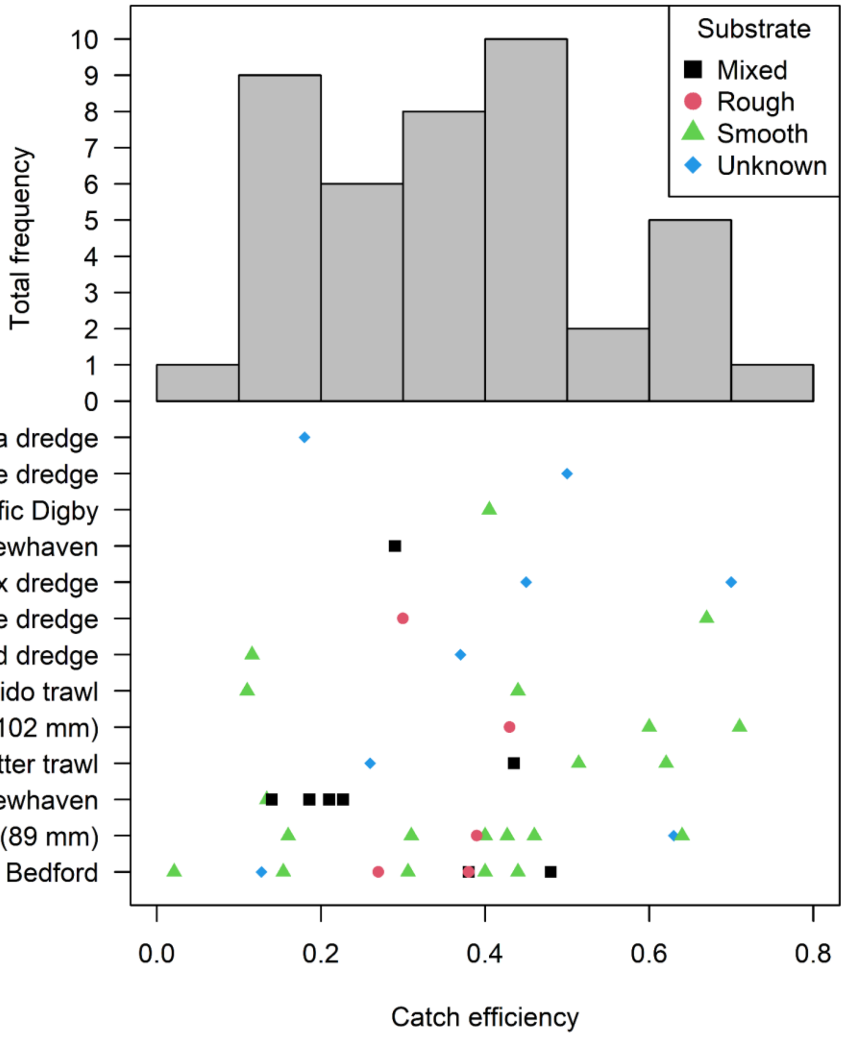

Figure 2: The bottom half of the plot displays size-independent estimates of catch efficiency by gear from individual studies. The shape of the points denotes the broad category of substrate type the study was conducted on, as indicated in the legend in the top half of the plot. The remainder of the top half of the plot is a histogram showing frequencies of catch efficiencies across gears to help complement the scatter plot on the bottom half. Therefore, both halves display the same data in different forms.

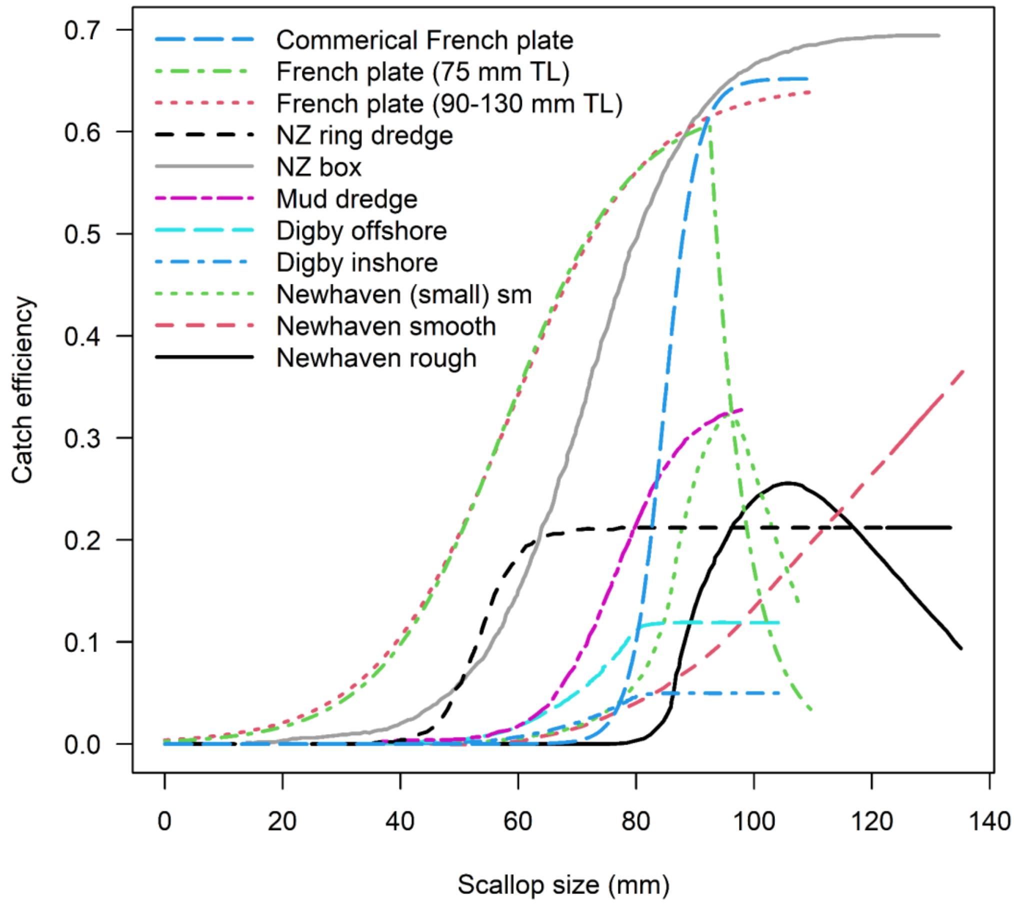

Figure 3: Recreations of size-based scallop catch efficiency curves reported for a range of towed gears under a range of conditions, where the y-axis is catch efficiency and the x-axis is scallop size in mm (either shell height or width, as reported by each study). The range of sizes each curve is presented across has been kept consistent with the source. The curves corresponding to French gear were presented in Fifas et al. (2004) and are recreated here using the parameter and equations provided in that study. Two of these gears are scientific dredges with varying teeth length (TL), and the third gear corresponds to estimates of commercial dredges. The line corresponding to New Zealand box dredges (NZ box) were presented in NIWA (2021). The single line for the NZ ring bag dredges was estimated by Tuck et al. (2018). The 'mud dredge' curve displays estimations for Australian mud/peninsula dredges by McLoughlin et al. (1991). The two Digby curves were recreated from Dickie (1955) and correspond to experiments conducted on commercial Digby dredges in inshore and offshore locations. Two of the Newhaven curves were recreated from Chapman et al. (1977) and Mason et al. (1979) and were obtained from two different vessels operating on different substrates (rough and smooth) using dredges with 1.22 m mouth width. The third Newhaven curve (denoted 'small') was obtained from Dare et al. (1993) and estimated on smooth substrate using dredges with 0.75 m mouth width. All curves apart from the French ones were recreated by digitizing the curves presented in the referenced studies.

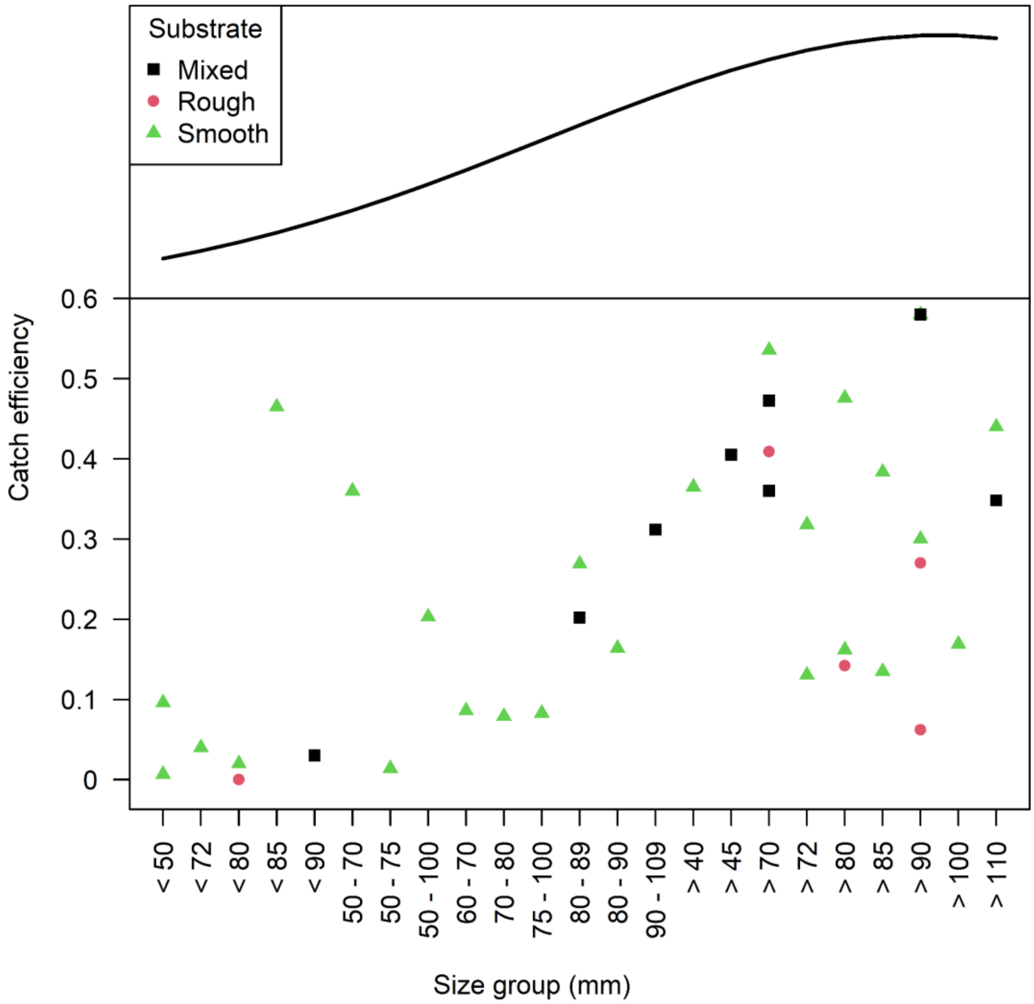

Figure 4: Size group catch efficiency estimates reported by individual studies displayed as a scatter plot. All size groups are measured in mm but may correspond to either shell height or width depending on the reporting in each study. All size groups are inclusive and those indicating less or greater than a value represent less/greater than or equal to. The shape of the points indicates the substrate type the estimate was derived on, which was classified based on the habitat language used in each study. The trend line in the top section of the plot is included to illustrate the trend in the scatter plot below.