doi:10.7289/V5/TM-SWFSC-545

NOAA Technical Memorandum NMFS

MAY 2015

NET SAVVY: A PRACTICAL GUIDE TO ZOOPLANKTON SAMPLER DESIGN

Eric M. Keen[1,2]

[1,2]Scripps Institution of Oceanography, 9500 Gillman Drive, Mail Code 0208, La Jolla, CA 92093-0208

Marine Mammal and Turtle Division
Southwest Fisheries Science Center, NOAA, 8901 La Jolla Shores Drive, La Jolla, CA 92037 USA, ekeen@ucsd.edu

NOAA-TM-NMFS-SWFSC-545

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

The National Oceanic and Atmospheric Administration (NOAA), organized in 1970, has evolved into an agency that establishes national policies and manages and conserves our oceanic, coastal, and atmospheric resources. An organizational element within NOAA, the Office of Fisheries, is responsible for fisheries policy and the direction of the National Marine Fisheries Service (NMFS).

In addition to its formal publications, the NMFS uses the NOAA Technical Memorandum series to issue informal scientific and technical publications when complete formal review and editorial processing are not appropriate or feasible. Documents within this series, however, reflect sound professional work and may be referenced in the formal scientific and technical literature.

doi:10.7289/V5/TM-SWFSC-545

NOAA Technical Memorandum NMFS
This TM series is used for documentation and timely communication of preliminary results, interim reports, or special purpose information. The TMs have not received complete formal review, editorial control, or detailed editing

MAY 2015

NET SAVVY: A PRACTICAL GUIDE TO ZOOPLANKTON SAMPLER DESIGN

Eric M. Keen[1,2]

[1,2]Scripps Institution of Oceanography, 9500 Gillman Drive, Mail Code 0208,
La Jolla, CA 92093-0208

Marine Mammal and Turtle Division
Southwest Fisheries Science Center, NOAA, 8901 La Jolla Shores Drive,
La Jolla, CA 92037 USA, ekeen@ucsd.edu

NOAA-TM-NMFS-SWFSC-545

U.S. DEPARTMENT OF COMMERCE
Penny S. Pritzker, Secretary of Commerce
National Oceanic and Atmospheric Administration
Dr. Kathryn D. Sullivan, Administrator
National Marine Fisheries Service
Eileen Sobeck, Assistant Administrator for Fisheries

Net savvy

A practical guide to zooplankton sampler design

Eric Keen [1, 2, 3]

[1] Scripps Institution of Oceanography, 9500 Gilman Drive Mail Code 0208, La Jolla, CA 92093-0208
[2] Marine Mammal and Turtle Division, Southwest Fisheries Science Center,
National Marine Fisheries Service, NOAA 8901 La Jolla Shores Drive, La Jolla, CA 92037 USA
[3] ekeen@ucsd.edu

Abstract

Plankton nets are widely used to sample phytoplankton, zooplankton and small nektonic animals. Here I present a step-by-step guide to designing plankton nets that fit the objectives of a study, the logistics of sampling, and the available budget. The primary three key parameters to determine in net design are mesh size, mouth diameter, and overall net length. These “key three” are related by the Open-Area Ratio (OAR), the ratio of effective filtering area to mouth area, which can be used to optimize sustained filtration performance for a target tow volume. Mesh size is determined first, which provides the expected porosity of the net and is primarily based on the smallest retained plankton size. Mouth size is then constrained according to avoidance capabilities of the target organisms and operational logistics. Overall net length is then set to achieve a target tow volume by meeting the minimum required OAR. All three factors can affect cost. Using this process, an array of potential net configurations can be evaluated. A case study is used to demonstrate this design process.

Introduction

Mesh nets are widely used to collect phytoplankton, zooplankton or small nekton, but no single net can sample all these organisms equally. Good net samplers must be designed with care, based on 1) the study objectives; 2) the conditions of your study area; and 3) the resources available to you. These considerations must be weighed to arrive at an appropriate design, which can be daunting for anyone limited by time or money. This guide is a decision-making tool to move from these fundamentals to a range of optimal design configurations.

This paper draws heavily from four sources: Tranter & Smith (1968), Harris et al. (2000, esp. chapters 2 and 3), de Bernardi (1984), and, most recently, Ohman (2013). Together these papers provide a broad theoretical foundation for all types of plankton samplers, study design and sample preservation. Here I present their principles in a practical, step-by-step guide by substantially limiting my scope to studies that require single- or dual-net samplers. Specifically the net models herein are based on the standard cylindrical-conical (“cyl-cone”) design advocated by UNESCO Working Party no. 2 (WP-2) .The WP-2 cyl-cone sampler has been a widely used design for small-scale zooplankton studies (typically for organisms 200 micrometers to 10mm in length) since its use was first proposed in the 1960s (Tranter & Fraser 1968, schematic on p. 155). While not universally ideal, the principles invoked here should be of use in a variety of applications.

My scope is further limited to three key design parameters: 1) aperture of the mesh material (i.e., mesh size), 2) diameter of the mouth, and 3) the net’s overall length. They combine to influence a net’s filtration efficiency and propensity to clog. They are also the most readily measurable when considering a candidate net. To illustrate each step of the decision making process I use my own case study: the design of a zooplankton net for use from a small vessel in the Kitimat Fjord System of northern British Columbia, Canada, in the territory of the Gitga’at First Nation (Appendix).

Background

Starting Points

To perform well and consistently, a good net must achieve the following:

1. Sample a target water volume before clogging degrades filtration efficiency (FE).
2. Retain the organisms targeted by the study’s objectives (minimize avoidance and escapement).
3. Filter a sufficient volume of water to provide statistically robust results.
4. Be operated safely with the available resources.

Filtration efficiency (FE)[1] is the percent of water a net passes through that is actually sampled. A net begins a tow with a maximum possible FE given its design (Initial, IFE), and Sustains FE (SFE) for a tow duration also determined by its design (detailed below). FE affects rates of net avoidance, escapement (organisms squeezing through the mesh), and clogging (Tranter & Smith 1968). Clogging diminishes volume sampled, introduces increasing size selectivity over the course of the tow, and generally biases results.

The Open Area Ratio

Designing for high FE means first maximizing IFE and then, within those design confines, maximizing SFE. The “open-area ratio” (OAR) is a metric of FE that, as the ratio of filtering mesh area to the area of the mouth’s opening, demonstrates the relationship between it and the key three design components[2]. The “filtering mesh area” refers to the total open area of the net’s mesh, which can be calculated by multiplying the net’s surface area by the mesh’s “porosity”, or percent open area.

$$OAR = \beta \frac{a}{A} \quad (1)$$

β = porosity
a = total area of net
A= mouth area

A net’s surface area can be calculated using the net’s geometry (shape, total length and mouth diameter). Note that mouth diameter influences both the numerator and denominator of the open-area ratio.

In general, the higher the OAR ratio of a net, the better for both IFE and SFE. Modest improvements in OAR can disproportionately change the effective tow duration (e.g., a doubling in OAR from 3.2 to 6.4 increases volume filtered sixfold; Smith, Counts and Clutter 1968). The rub, however, is that other concerns constrain a net’s design such that a sufficient OAR can be difficult to attain. Net selection is therefore a game of trade-offs, driven by the conflicting priorities of maximizing OAR, maximizing sample size, and minimizing cost and effort.

Initial Filtration Efficiency (IFE)

The shape of a net and the way it is used will determine its IFE. A higher IFE means better use of sampling effort and more flexibility in the steps to come. IFE values for conventional net types range from 75% (simple conical nets) to upwards of 110% (reducing collar cyl-cone nets). The WP-2 has an IFE of 94% (Tranter & Fraser 1968). Some design for 100% IFE to simplify calculations (Tranter & Smith 1968).

Net Shape
A net’s geometry governs the way in which water flows through and around it. The hydrodynamics of this flow are sensitive to a slew of variables (reviewed in Tranter & Smith 1968) and can be summarized with the following principles of design:

Simple cones: Simple conical nets are among the least efficient, at about 75-85% IFE. They need to be longer (higher OAR) to sample as effectively as a cylindrical-conical net of similar shape.

Nonporous encasements: Nets housed within nonporous encasements are 40% less efficient and should be avoided. Their low IFE is due in part to the angular deformation of flow at the encasement wall (Tranter and Smith 1968; see Fig. 6d therein).

[1] Tranter & Smith (1968) abbreviated filtration efficiency as F. In an effort to emphasize the distinction between initial and sustained efficiency, I use a different notation here.

[2] In Tranter & Fraser (1968) and other works, the open-area ratio is abbreviated simply as R. Here I follow Ohman (2013).

Cylindrical collars: Both IFE and SFE increase when a porous cylindrical section of mesh is added ahead of the cone. Water rejected by the tapering area of the cone can escape through the cylinder's mesh rather than out the mouth where animals would be lost (Currie 1963). A cylindrical collar also adds more filtering area while adding less to the overall length of the net than a conical form would. That is, a cyl-cone net has a higher OAR than a conical net of the same length. A cyl-cone design is the model I use in this paper (Fig. 1).

Non-porous collars: Non-porous collars, which may be necessary for some nets with choke lines (e.g., plummet nets, Heron 1982), can also yield high IFEs (Tranter and Smith 1968). Note, however, that the length of a non-porous collar cannot contribute to the filtering area used in OAR calculations for the design; i.e., a non-porous cyl-cone net may be more efficient but it will have to be longer. Both porous and non-porous cylindrical collars alike tend to oscillate slightly underway, inducing a "self-cleaning" behavior (Smith and Clutter 1965).

Mouth-reducing collars: Enlarging the terminal radius of the cylindrical section to create a "mouth reducing collar" creates an area of low pressure behind the net mouth into which incoming water will accelerate (Fig. 6c in Tranter and Smith 1986). This increases IFE to 110% or more, among the most efficient of any design (Smith, Counts, and Clutter 1968). However, they are less commonly available and the goal in this paper is to determine minimum pragmatic requirements.

Side angles. IFE declines sharply when the net's side angle -- the angle of incidence of water striking the mesh (Θ in Fig. 1) -- falls below 75° or when the ratio A/a rises above 0.2. It is therefore important to maximize side angle, which translates into increasing net length.

OAR has limited effect on IFE. As outlined above, the boosted IFE of a cyl-cone net can be explained by both mechanical effects (e.g. self-cleansing) and the higher OAR that comes with the addition of filtering area. However, hydrodynamic theory explains that improving OAR only boosts IFE up to a certain point, and the effect plateaus above an OAR of 3 (Tranter & Smith 1968). Instead, OAR becomes much more influential in matters of SFE (next section).

Tow Speed

Tow speeds slower than 1 knot (0.5144 m/s) will dramatically reduce FE (Tranter & Smith 1968). In the case study's literature review (Table 2), most tow speeds were between 0.77 m/s (Fiedler et al. 1998) and 1.28 m/s (Mackas & Galbraith 2002, Schulenberger 1978). The median tow speed reported was ~1 m/s. WP-2 recommended that vertical hauls be raised at 0.75 m/s (Tranter & Fraser 1968). Down-sampling "plummet" nets are weighted in order to fall at desired speeds, and published fall rates range from 0.7 m/s (Hovekamp 1989) to 1 m/s (Daly & Macaulay 1988; Daly 1990) to 1.5 m/s (Heron 1982).

Higher tow speeds (> 1.5 m/s) may allow for shorter tow durations and may minimize avoidance (although fast tow speeds may induce bow waves ahead of the sampler, warning target organisms; Clutter & Anraku 1968), but pressure drop across the mesh at high speeds can damage specimens (Tranter & Smith 1968). Sampling efforts for live experiments or morphological studies in particular should prioritize minimal tow speed. High tow speeds can also strain deck equipment.

Washing & Care

Net maintenance and care also affect IFE, since the presence of remnant plankters and debris in successive tows can introduce variable IFEs over the course of a study (Tranter & Smith 1968). Thorough rinsing between tows with filtered seawater and at the end of a survey day with freshwater is critical. Plankton dry more completely on monofilament nylon mesh, which is now the industry standard, compared to older silk designs. Harris et al. (2000) outlines best practices for net care and storage.

Sustained Filtration Efficiency (SFE)

Clogging will cause the net's FE to deteriorate, introducing more and more bias by reducing overall filtration efficiency and selectively sampling a progressively constrained size range of organisms (Ohman 2013). By convention, once FE has dropped below 85% of IFE, the net has become clogged (Smiths, Counts & Clutter 1968). Sampling enough water before this occurs is the central goal. The rate at which clogging occurs is a function of the conditions of the study area (over which we have little control) and the design of our net.

Clogging can be monitored by comparing readings from two flowmeters, one mounted inside and the other outside of the net during a sequence of variable-duration tows (Tranter & Smith 1968).

SFE is governed by the key three OAR variables, but net shape can also have an affect. As explained above, the geometry of a net can introduce "self-cleaning" oscillations that increase the duration of efficient filtration. A cylindrical or mouth-reducing section can also add filtering area to the net, increasing OAR and therefore SFE.

Mesh Size

The width of mesh holes influences SFE in two ways. First, fine gauze will clog more readily than coarse gauze merely because it catches more particles. The effective tow duration of a net increases as a function of the square of the mesh size (Smith, Counts & Clutter 1968). In order to compensate for the inherently high clogging rate of fine mesh nets, OAR must increase substantially. For mesh sizes > 300μ, Tranter & Smith (1968) recommend an overall OAR of 5 or higher, with an OAR of 3 in the conical portion and an OAR of 2 in the cylinder. Smaller mesh would require an OAR of 9 or higher, with 3 in the cone and 6 in the cylinder. However, in the same monograph, WP-2 proposed a standardized net schematic with 200μ mesh that had an OAR of only 6:1, 3 in the cylinder and 3 in the cone (Tranter & Fraser 1968). To err on the conservative side (*sensu* Ohman 2013), here I hold minimum OAR for mesh apertures < 300μ at 9:1.

Second, mesh size determines a net's porosity: the proportion of the material that is open. While one might expect porosity to decrease linearly with shrinking mesh size, different Nylon monofilament widths are used in weaves for various apertures, resulting in unpredictable porosity curves. Furthermore, mesh of the same aperture can be available at different porosities (Fig. 2). Weave strength is not of great concern for small-scale studies with low tow speeds, so it is worthwhile to seek out the most porous version available of your required mesh size. Doing so may allow a net to be shorter[3].

Net Model

Parameter Bounds

To maximize IFE, I will 1) only consider configurations that yield an OAR greater than 3 and 2) hold the minimum side angle of the net at 81.33° to match the WP-2 design (minimum allowable is 75°; Tranter & Smith 1968). Thus, each candidate diameter has a corresponding minimum length. Average tow speed used in tow duration calculations will be 1 m/s (2 knots, min=0.5m/s, max=1.5m/s). The average IFE for conventional cyl-cone net configurations reported by Tranter & Smith (1968, Table 5, n=7) was 94.43% ± 2.99%. To remain conservative, our model will have an IFE one standard deviation below that mean, at 91.4%.

Geometry

See Fig. 1 for the geometry of the model net used in this guide and Table 1 for a definition of its parameters.

Cod-end: Because nets reduce not to a point but to a terminal cod-end bucket, net "cones" are actually tapered cylinders. The mean cod-end radius of 63 nets sampled from the Scripps Institution of Oceanography Pelagic Invertebrate Collection (SIO PIC) was 5.48cm (sd=2.1cm) (Linsey Sala, pers. comm.). A cod-end of radius 3.75cm was recommended by the WP-2 (1968), which is a value within the standard deviation of the PIC sample. Because the WP-2 radius ensures the model will err on the side of underestimating OAR, it will be used as the radius in the model net.

Collar length: Because the cylindrical section contributes much to overall OAR with a comparatively minor addition of total length, the cone's length will be minimized. With the side angle minimized, we can calculate the length of the conical section (ℓ_{con}) of any net by knowing only the radii of its mouth (*R*) and cod-end (*r*, given above as 3.5cm).

$$\ell_{con} = \tan\theta(R - r) \tag{2}$$

[3] Mesh aperture and porosity can be difficult to know if a net does not come with documentation. Smith, Counts, & Clutter (1968) provide instruction on measuring and calculating these values using a microscope.

The cylindrical section will comprise the remainder of the net's overall length, meaning that low OAR nets will have proportionally longer conical sections. In nets with an OAR >= 10, the majority of its length will be composed of cylindrical section. In fact, the length ratio of the cylindrical and conical sections may swing from 2:3 to 6:3 as net length increases (Smith & Clutter 1965, Tranter & Smith 1968).

The overall length (ℓ_{tot}) will be the sum of the cylindrical and conical sections (ℓ_{cyl} and ℓ_{con}).

$$\ell_{tot} = \ell_{con} + \ell_{tot} \quad (3)$$

Similarly, the total filtering area (*a*) will be the sum of the lateral surface areas of each section (a_{cyl} and a_{con}).

$$a = a_{cyl} + a_{con} \quad (4)$$

Using conventional geometric equations, these surface areas are calculated as follows:

$$a_{cyl} = 2\pi\ell_{cyl} \quad (5)$$

$$a_{con} = \pi s(R + r) \quad (6)$$

Where *s* is the side length of the conical section, which can be thought of as the hypotenuse of a right triangle with sides of length ℓ_{con} and R – r. As such, the Pythagorean relationship applies:

$$s = \sqrt{\ell_{con}^2 + (R - r)^2} \quad (7)$$

These equations will be used to calculate overall length, which shall be the last free variable after diameter, mesh size (porosity) and OAR are constrained. To checked the above equations with the WP2 schematic provided in Tranter & Fraser (1968). The schematic displays a net with 200μ mesh aperture, 0.57m diameter, .95m cylinder length, 1.66m side length (different from cone length), and an OAR of 6:1. The WP2's total length is the sum of its two section lengths, 2.59m. The porosity for this mesh size is reported as 45% by Dynamic Aqua Ltd. (Fig. 2; the same value is given in Table 4 in Tranter & Smith 1968). By assuming this net has a 0.075m diameter cod-end, simple geometry can be used to calculate the cone's side angle (81.33°) and the length of the cone (1.64m). Using only the mesh size, diameter and OAR reported in the schematic, the above equations calculated that the overall length of the net would be 2.566m, with 0.961m in the cylinder and 1.604m in the cone. These values are within 2% of the actual dimensions.

Designing the Net

The coupled interactions of the "key three" parameters (diameter, length, and mesh size) are such that several different configurations can result in the same OAR. They must therefore be constrained in a certain order. The figures associated with each step below provide a quick way for readers to work through the process with their own study in mind.

Step 1: Organizing Questions

Appropriate net design first requires that you rigorously define your objectives and familiarize yourself with your study area. Specific answers for the following questions will direct the remainder of the process.

1. **Target questions and taxa:** Target organisms and life stages should be known with inordinate specificity. Do the study's motivating questions have to do with the diversity of an area, the density or abundance of certain species, the distribution of those species in space or time, or a combination thereof?

2. **Study area:** Where is the study area, and what bathymetric, geographic, and oceanographic features should be taken into account during study design? Are the waters very shallow or deep? Are there narrow channels? Are the waters turbid and productive ("green waters") or clear and free of suspended debris ("blue waters"), or can they be either depending on recent conditions? Will the weather be extremely cold and wet?

3. **Resources:** How will field conditions and equipment constraints limit the sampling plan? Will the net be deployed and retrieved manually, or with mechanical help? Is there adequate deck space for deployment and sample preservation?

4. **Design:** What kind of sampling design do these goals necessitate? Day-time or night-time sampling? Vertical tows or oblique tows? What sampling frequency and coverage need to be planned for?

Step 2: Mesh Size

With target groups and life stages in hand, net mesh size can be determined. Mesh aperture must be small enough to retain the smallest of target organisms, but no smaller than necessary since the secondary goal is to avoid clogging as long as possible. Mesh size will determine minimum OAR (see "Background") and expected mesh porosity (Fig. 2).

Step 3: Diameter

Diameter occurs in both area terms of the OAR equation, causing its impact on OAR to be nonlinear and dependent upon the porosity of the mesh size. Choice of mouth diameter is informed by both target organism behavior and available resources.

Net avoidance – zooplankton actively dodging the net -- is a serious concern in mesozooplankton studies and its severity depends upon many factors (Weibe et al. 1982) including time of day (Fleminger and Clutter 1965); light regime (Isaacs 1965); size, shape, and color of the net (McGowan and Fraundorf 1966); speed of tow (Brinton 1967); species (Clutter and Anraku 1968); sex or developmental stage of the organisms; their physiological state (Laval 1974); and absolute density (Boyde et al. 1978). Avoidance is of special concern for euphausiids (Brinton 1962). While avoidance effects may be mitigated during analysis with correction factors (e.g. Mackas et al. 2000), here the question is how the key three parameters can be configured to optimize net performance.

The risk of avoidance makes large nets better at sampling certain taxa representatively (Pearcy 1983, Tranter 1963), especially for rarer species (McGowan & Fraundorf 1966). McGowan & Fraundorf (1966) focused on the efficacy of different net sizes in sampling for diversity and abundance, and the susceptibility of various designs to biases introduced by species patchiness and avoidance ability. Mouth diameters in their study ranged from .2m to 1.4m. Their sampling design held other variables constant, including mesh size (550 micron), tow speed (3.4 km/hr, 1.85 knots, 0.9 m/s) and volume sampled, in order to observe the sole effect of mouth opening diameter on net efficacy. Their analyses also disaggregated biases due to the patchiness of plankton aggregations from those due to active avoidance. The size of the sampling device did in fact have an effect on estimates of zooplankton diversity. The nets sampled diversity in the following ranked order of mouth diameter: 1.4 > 1.0 = 0.4 = 0.8 > 0.6 > 0.2m. The nets sampled abundance in the following rank: 1.4 > 1.0 > 0.8 > 0.6 > 0.4 > 0.2 m.

Bigger may seem better, but there are also reasons to minimize diameter: a larger mouth means a longer net, which is more costly, more cumbersome with more drag while underway. This would change cable angle for a given tow speed (Tranter & Smith 1968), requiring more cable to sample the same depth. Large-diameter nets may sample large volumes over shorter distances, and they may minimize avoidance effects, but they are also more susceptible to the effects of patchiness (McGowan & Fraundorf 1966). Use of large nets can also be limited by deck space, towing hardware, and the stamina of the crew. In the end, one must decide what to gain and what to lose based on objectives, the study area, and resources.

Step 4: Tow Duration

Net length is the remaining design component in question, but to constrain it some ancillary issues must first be addressed. The first is target volume, which will be informed by knowledge about target taxa habitat preferences and study area conditions. A sufficient tow volume ensures adequate sample size for statistical analyses. Assuming no clogging occurs, the volume sampled (V) by a tow of a certain distance (D) is determined by the net's mouth area (A) and its initial filtration efficiency (IFE):

$$V = IFE \cdot A \cdot D \tag{8}$$

Constraints from Sampling Design

If you are interested, for example, in the horizontal distribution or patchiness of zooplankton aggregations, dividing your effort into a sufficient number of shorter tows rather than a single long tow may be more appropriate. Unfortunately this can drain preservation supplies and crew morale.

Insights from the Literature

Most of the regionally relevant zooplankton studies did not report tow volumes. Exceptions were Mackas & Anderson (1986), who used a small diameter net for short oblique tows of 4-10m^3 in a mesozooplankton survey, and Miller et al. (1984), who used a stratified vertical sampling regime. Based on their reported net size and towing distances, I estimated that their tow volumes ranged from 50 to 380 m^3. McGowan & Fraundorf (1966), in their study of net size efficacy, shot for a standard sampling volume throughout their tows of single nets with various mouth sizes. They averaged 368.65 m^3 per tow (n=24 tows), with a standard deviation of 74.12 m^3. Schulenberger (1978), in his study of central gyre hyperiid amphipods, had a target sample volume of 400 m^3. Jerde (1967), who used a 1m^2 net towed obliquely at 1-2 knots for an average of 14 minutes to sample euphausiids, sampled from 385 to 468m^3.

The CalCOFI study has been conducting zooplankton tows at a grid of stations in southern California waters since 1949, the results of which are publicly available online (http://www.calcofi.org). This study operates from large oceanographic vessels, employs a variety of nets for different purposes, and has used different equipment over the course of its history (Ohman & Smith 1995). Investigators increased tow depths to 210m in 1969, and switched from a 1.0m bridled single net to a 0.71m bridle-less BONGO net in 1969 (both with 510-550µ mesh)(Ohman & Smith 1995). However, their scientific objectives have remained more or less the same, and there is much that small-boat studies can learn from their records. Between 1951 and 2012 their 46,502 tows for large mesozooplankton have yielded an average tow volume of 434.7 m^3, with a standard deviation of 147.5 m^3 (Fig. 3).

Constraints Imposed by Study Area

If, like this paper's case study, sampling must occur within a complex of narrow coastal channels, long oblique tow distances may not be an option. All North Pacific studies of our primary taxa of interest (euphausiids and calanoid copepods) that used oblique tows sampled no shallower than 100m (Coyle & Pincuk 2005) and as deep as 500m (Trevarrow et al. 2005).

Vertical tows are constrained more by water depth than by channel width. Among the papers I reviewed those using vertical tows had the following operating depth ranges: 100m (Coyle & Pincuk 2005), 185 m (in a fjord, Osgood & Frost 1994) and 250m (in a fjord, Tanasichuck 1998; Mackas 1992), and 1000m (Miller et al. 1984).

Practical Proxies for Tow Volume

For small boats it is typically impossible to know the volume of water that was sampled in a tow until you retrieve the net and check the flowmeter. In practice, therefore, a proxy for volume sampled such as tow distance or duration must be used to decide when to end a tow. This requires a means of translating among tow volume, distance, and duration, which can be done by equating the distance term in the conventional rate equation,

$$r_{tow} = \frac{D}{(t_{end} - t_{start})} \tag{9}$$

where

r_{tow} = tow speed-over-water
D = distance of tow
t_{end} = end time of tow
t_{start} = start time of tow,

to that in the volume equation (Eq. 8), then solving for volume sampled (V). The result:

$$V = A\, r_{tow}(t_{end} - t_{start})\, IFE \tag{10}$$

Assuming that no clogging occurs during a tow at 1m/s speed-over-water and that IFE is no worse than 85%, we can then predict the volume we sample from the duration of our tow (Fig. 4). An example of such relationships can be seen in the CalCOFI dataset (Fig. 5). With their net configurations, the average tow volume of ~430 m^3 was obtained after approximately 15 minutes of towing (but note the bimodal distribution; two protocols may have been used).

In order to correct for the effect of water current on the “apparent” tow speed of your net, it is important that speeds are recorded as speed over water. If speed over water is known, simple calculations provide a more practical proxy for volume that can be incorporated into protocols, though these do not replace calibrated flowmeters mounted on the net.

Results
Once a maximum sampling volume is determined, Fig. 6 can be used to translate between tow distance and sample volume for various mouth diameters. From this a range of expected tow distances can be determined, which will then be used to determine the minimum OAR required of the net.

Step 5: Minimum Open-Area Ratio

Determining minimum OAR (MOAR) is the last task before one can decide upon an overall length. Because all studies are confined by logistics and limited resources in some respect, determining the true minimum OAR for a specific study is invaluable as one weighs the feasibility of sampling design and explores the equipment options available.

That MOAR for a net can be set by the IFE and requisite mesh size has already been demonstrated in the “Background”. Target volume can also establish the MOAR. Clogging becomes a bigger issue the further a net is towed, at a rate that depends on area turbidity. In coastal “green waters” that are nutrient and detritus-rich, clogging occurs faster than in offshore “blue waters” and therefore require a higher OAR. The relationship between MOAR and distance towed (by proxy, the volume sampled) has been described by two equations (Smith, Counts and Clutter 1968):

For “Green waters”:

$$\log OAR = 0.38(\log \frac{V}{A}) - 0.17 \tag{11}$$

For “Blue waters”:

$$\log OAR = 0.37(\log \frac{V}{A}) - 0.49 \tag{12}$$

Where V is the volume of the sample and A is the area of the mouth opening. The V/A term (which is equivalent to distance towed if IFE is assumed to be 100%) allows you to proceed if some parameters are not narrowed down. If your area can experience both “green” and “blue” conditions, e.g. a coastal station where upwelling can seasonally alter productivity, you must design with the “greenest” conditions in mind.

For each net diameter under consideration, find the distance you must tow in order to achieve the maximum sampling volume you hope to accommodate. Bring these distances to Fig. 7 to determine minimum OAR.

Step 6: Net Length

With mesh size and porosity, mouth diameter, target volume and MOAR in hand, you can now explore the length options that make your MOAR possible. Length is constrained last because mesh size and diameter stem directly from the basal objectives of the study. There are logistical reasons to minimize net length, including high cost of mesh yardage, loss of deck space, and higher drag, but it is better to err on the longer side than to invalidate your study.

In Fig. 8 you can go to the frame that corresponds to your net's minimum OAR. On the y-axis is the porosity range that corresponds to the mesh size of the net. Identify the color-coded lines that best match the candidate diameters. The point of intersection of diameter and porosity lay over the necessary length for the net (x axis).

Rarely will the answer be cut and dry; most will approach this final step with a range of mesh sizes and diameters still under consideration. It often requires returning to the roots of this process to weigh the candidate configurations against each other. If the required net length is prohibitive, the constrained parameters should be reconsidered in the reverse order that they were pinned down: first sample volume (Tranter & Smith 1968), then diameter, and finally, mesh size. If you must resort to changing the mesh aperture of your net, then the overall feasibility of your study may need to be reconsidered.

Next steps

There is much more to appropriate net design than mesh size, diameter, and length. Many have been encountered during the above process: net shape, tow speed, maintenance regime, rigging considerations, strobe lights, etc. There is also the fundamental question of whether a net is a better sampler than bottles or optical or acoustic methods in the first place (Ohman 2013 and Harris et al. 2000 are excellent resources here).

This guide's scope was limited to the "key three" features because 1) it addresses the need for a paper that provides a clear starting point for the net design process, 2) those three features are what determine FE, 3) they are the most readily obvious features of a net, and 4) if investigators can gain the understanding required to constrain them, they will be empowered to grapple with the other aspects of net design with more confidence. It is then a mere matter of obtaining the net and putting it to good use.

Acknowledgments

I thank Linsey Sala and Mark Ohman, collections manager and curator of the SIO Pelagic Invertebrates Collection, respectively, for their advice, guidance and access to data regarding their inventory of nets. This memorandum was greatly improved by its reviewers, and it would not have been published without the encouragement and guidance of Jay Barlow, Paul Dayton, Dave Checkley, Keri Bryan and Lynn Evans. The net that resulted from this design process was funded by National Geographic Waitt-Grant W268-13. I conducted this work under the support of an NSF Graduate Research Fellowship (DGE-114086) and NSF GK-12 Fellowship. The case study described is possible via a research agreement with the Gitga'at First Nation and a research permit with Fisheries and Oceans Canada (XR 65 2013 and XR 83 2014).

Appendix: Case Study

To illustrate each step of the net design process, below I detail a case study set in the Kitimat Fjord System of northern British Columbia, Canada (Fig. 9). The study's primary objective is to document trophic interactions between rorqual whales and their prey from a 12m motorsailer. A feasibility study was conducted in 2013 and full research seasons were conducted in 2014 and 2015. This work was in close collaboration with the Gitga'at First Nation, the North Coast Cetacean Society and Fisheries and Oceans Canada.

Step 1: Organizing Questions

Objective

The primary objective of this study was to document trophic interactions between large cetaceans, primarily fin whales (*Balaenoptera physalus*) and humpback whales (*Megaptera novaeangliae)*, and their prey. The goals regarding zooplankton were as follows:

1. Monitor seasonal trends in relative density and patchiness of dominant zooplankton using echosounder imagery, ground-truthed by vertical tows.
2. Describe geographic patterns in shifts in zooplankton diversity and dominant taxa - namely, comparing communities from “far outer” (corresponding to samples from Caamano Sound and Estevan Sound), “central outer” (Squally Channel and Campania Sound), “central inner” and “far inner” (Verney Sound and Ursula Channel) waterways (Fig. 9).
3. By examining tow and echosounder results in the context of water column samples and predator surveys, describe zooplankton dynamics within the context of both “bottom-up” (environmental) and “top-down” (competition and predation) interactions.

Target Groups

Target groups for this study were chosen by consulting published studies of cetacean diet and zooplankton ecology from the region. I wanted to prioritize sampling for the species that resident whales were known to feed upon, as well as those species preyed upon by their prey. In summary the primary targets of my study were *Euphausia pacifica*, *Thysanoessa spinifera* (all life stages), and the copepods *Neocalanus cristatus, N. plumchrus, N. flemingeri, Calanus marshallae,* and *Metridia lucens* (late naupliar and copepodite stages). Secondary targets included hyperiid amphipods, chaetognaths and larvaceans. In addition to representing the primary zooplankton prey of resident whales, these taxa were also the dominant taxonomic groups of B.C. waters, monitoring their dynamics would also reflect general zooplankton community dynamics in the study area.

Study Area

The study area (Fig. 9) in northern British Columbia is a complex of fjords that results in a broad intracoastal archipelago with deep channels bookended with sills. Broadly, the northwest coast has been an active area of study regarding the influence of oceanographic processes on zooplankton community dynamics (Mackas & Coyle 2005), but no zooplankton survey has yet been conducted in this remote sector of the British Columbian coast. Its waters are productive (“green”). Strong tides and terrigenous sources of freshwater and nutrients result in impressive currents and onshore-offshore gradients in salinity and temperature. Like most fjords, the physical properties of its upper water column are highly structured.

Field conditions ranged from comfortable to near-freezing downpours and thick fog. Thanks to the area’s protected waterways, swell was only of concern at the outermost sampling stations. Seafloor depth varied widely and shallow (~32m) sills were present at several channel constrictions.

Resources

Resources for this study were limited. It was a small operation, crewed by three researchers aboard a 12m motorsailer. Tows were to be retrieved with a commercially available line hauler (Powerwinch Pot Hauler, 150 lb capacity) used in conjunction with the vessel’s 72” davit. Confined deck space limited us to a single-net design, and other study objectives limit the time we could devote to tows. 250m of 3/8” double-braided nylon towline were stowed in a square recycling bin lashed to the transom rail.

Study Design

To design for my goals within our constraints, I planned for daytime vertical tows with nets that sample as they fall (“plummet nets”, after Bartle 1976, Bradford 1977, Heron 1982, Daly & Macauley 1988) and Hovekamp 1989, among others). In plummet nets, weight is another critical element of design that must be chosen carefully. The net’s total drag (a function primarily of mouth diameter) and the mouth ring’s weight determine fall rate, which needs to remain between 1 m/s and 1.5 m/s in order to catch euphausiids. Larger nets require heavier rings; Heron’s (1982) plummet net is a WP2, 0.57m diameter, and needed to weigh 24kg in order to fall at 1.5 m/s. Anything heavier is difficult for a small crew to operate without machinery. The appropriate weight was determined using the trial methods outlined in Heron (1982).

These tows complemented the prey maps generated using an echosounder recording during systematic transects (Fig. 10). Infrequent night tows were attempted when possible, but the risks associated with nighttime intracoastal navigation limited their number.

Step 2: Maximum Mesh Size

I scrutinized the methodologies of the zooplankton literature relevant to my case study region and target taxa (Table 2), and concluded that the limiting target taxon in the area is the copepods. All life stages of euphausiids, amphipods, and chaetognaths can be sampled with 333μ mesh or even larger. This mesh size seems a standard among regional zooplankton studies. Some copepod studies have also used 333μ mesh (Mackas & Anderson 1986, Miller & Clemons 1988, Miller et al. 1991, Tsuda et al. 1999, Tsuda et al. 2001). However, these studies focused only on the late copepodite stages of target species, with the exception of Miller & Clemons (1988) who employed another net with smaller mesh size (70μ) to quantify egg and naupliar stage dynamics. If we wished to collect mid- to late-naupliar stages of our target copepods, if only for descriptive results, nothing larger than a 220μ mesh should be used -- and the smaller the better (after Mackas 1992, Mackas & Galbraith 2002, Peterson 1979, Trevorrow et al. 2005). But, given all the other dimensions of this study that required attention and the large amount of samples we hoped to accumulate over the season, our focus had to be limited to copepodite stages. My maximum mesh size was therefore be 333μ. According to Fig. 2, the porosity of 333μ mesh is 46% from both suppliers.

Step 3: Diameter

Concerns of avoidance by euphausiids (my primary targets) governed my diameter decision. Avoidance is a relatively negligible concern in copepods and amphipods. Most of the regional literature (Table 2) involving euphausiids used net sizes between 0.6m and 1.0m in diameter (Fiedler et al. (1998)'s 2.94m net was an exception, but their field work was done from a large oceanographic vessel). The WP-2 small mesozooplankton net is 0.57m in diameter (Tranter & Fraser 1968), which may be too avoidable for euphausiids. Harris et al. (2000) recommended a diameter of 0.70m in temperate coastal zones (with a 200μ mesh). Given my focus on euphausiids, anything less than 0.7m would not do. However, beyond a diameter of 1m weight, deck space, and drag would become prohibitive. A large mouth would also constrain other parameter options in the effort to maximize OAR. The best range for this case study was therefore a diameter of 0.7m to 1m.

Step 4: Tow Duration

Many factors were considered for tow duration, given that 1) tows contributed most to my objective of sampling diversity, 2) safety concerns confined me to daytime sampling, 3) zooplankton distribution is generally structured more vertically than horizontally, 4) many vertically migrating taxa may be at depth during the hours I would be sampling, 5) time and crew resources were considerably limited, and 6) several other study objectives required attention while the vessel is underway. Replicated vertical tows therefore seemed most appropriate. A sufficient volume had to be sampled in each study zone (outer, central outer, central inner, and inner) in order to provide robust comparisons of community composition.

Because target volumes in vertical tows were usually reached by repeated casts and not by tow distance, the duration of each tow was determined by the station depth and the available length of towing line. The latter was limited by deck space and the pot hauler we used. Seafloor depth was generally not a limiting factor, as the centers of fjord channels in our study area can be 600m deep or more, though 75-150m sills are also present. With a 250m line the drift of the vessel away from the falling net due to winds and tidal currents would reduce the effective tow depth to little more than 200m. This is comparable to published methods (Table 2), and should sufficiently sample deeper daytime scattering layers of dominant taxa. Therefore we expected our tows to reach an average of 200m depth, which with a diameter range of .70m - 1.0 m and a 91.4% initial sampling efficiency would yield volumes between 75 and 143 m^3 (Fig. 6a). These values meet or exceed published vertical tow volumes (Table 2), but they are low compared to mean oblique tow volumes from CalCOFI (434.7 m^3) and McGowan & Fraundorf (1966; 368.65 m^3), among others.

Replicate tows would be needed to sample a target volume of 400 m^3. With a .70m net, a minimum of 6 casts would be required. With a 1.0m net, I would need 3 casts. To prioritize sampling for diversity in the four study zones, these tow replicates would be dispersed (Fig. 10).

Step 5: Minimum Open-Area Ratio

Minimum OAR for any net is 3:1. If I opted for 333μ mesh, I would boost that minimum to 5:1. Because my study was in green waters, my desired vertical tow duration of 250m required an OAR of 5.3:1 (Fig. 7). If I had used 150-230μ mesh to catch naupliar copepods, my minimum OAR would have been set not by tow duration but by mesh size itself at 9:1.

Step 6: Solving for Net Length

With known MOAR, porosity and diameter options in hand, I could constrain net length. I was working with 3 diameter options, 0.70m, 0.85m, and 1.0m, yielding three potential configurations (Fig. 8).

1. 333μ (46% porosity), 0.70m, 5.3:1, 2.80m length.
2. 333μ (46% porosity), 0.85m, 5.3:1, 3.5m.
3. 333μ (46% porosity), 1.0m, 5.3:1, 4.1m.

Given the small size of our research platform, Option 1 was the best choice for me. This net necessitated a minimum of 6 casts in each zone (outer, central outer, central inner, and inner) to compare their community compositions robustly.

Because mine was a plummet net design whose cylindrical collar was cinched with a choke line, the collar must be non-porous and cannot contribute to the 2.8m of length needed to achieve an OAR of 5.3:1. The collar must at minimum be the length of the mouth's diameter, giving an overall net length of 3.5m (Fig.11, 12).

Literature Cited

Andersen, V. 1998. Salp and pyrosomid blooms and their importance in biogeochemical cycles, p. 125-137. In Q. Bone [ed.], The biology of pelagic tunicates. Oxford University Press, Oxford.

Bollens, S.M., B.W. Frost, B.W., and T.S. Lin. 1992. Recruitment, growth, and diel vertical migration of Euphausia pacifica in a temperate fjord. *Marine Biology* 114: 219–228.

Bone, Q., H. Kapp, and A.C. Pierrot-Bults. [ed.] 1991. The biology of chaetognaths. Oxford University Press, Oxford. p. 1-173.

Boyde, S.H., P.H. Weibe, and J.L. Cox. 1978. Limits of Nematoscelis megalops in the Northwest Atlantic in relation to Gulf Stream cold core rings. II. Physiological and biochemical effects of expatriation. Journal of Marine Research 36:143-159.

Brinton, E. 1962. Variable factors affecting the apparent range and estimated concentration of euphausiids in the North Pacific. Pacific Sci., 16:374-408.

Brinton, E. 1967. Vertical migration and avoidance capability of euphausiids in the California Current*. Limnology & Oceanography* 12:451-483.

Brinton, E., M.D. Ohman, A.W. Townsend, M.D. Knight, and A.L. Bridgeman. 2000. Euphausiids of the World Ocean. *World Diversity Database CD-ROM Series.* Windows Version 1.0. ETI Expert Center for Taxonomic Identification: Mauritskade, Netherlands.

Calkins, D.G. 1986. Marine Mammals. In Hood, D.W., and S.T. Zimmerman, eds. 1986. The Gulf of Alaska: physical environment and biological resources. NOAA Alaska Office OCS Study MMS 86-0095.

Clutter, R.I., and M. Anraku. 1968. Avoidance of samplers. In *Zooplankton Sampling*, p. 57-76. UNESCO Moograph of Oceanographic Metholodies 2.

Cooney, R.T., 1986. Zooplankton. In: Hood, D.W., Zimmerman, S.T. (Eds.). *The Gulf of Alaska, Physical Environment and Biological Resource.* MMS/NOAA, Alaska Office, Anchorage, OCS Study MMS 86-0095, pp. 285–303.

Coyle, K.O., and A.I. Pinchuk. 2003. Annual cycle of zooplankton abundance, biomass and production on the northern Gulf of Alaska shelf, October 1997 through October 2000. *Fisheries Oceanography* 12, 327–338.

Coyle, K.O., A.I. Pinchuk. 2005. Seasonal cross-shelf distribution of major zooplankton taxa on the northern Gulf of Alaska shelf relative to water mass properties, species depth preferences and vertical migration behavior. *Deep-Sea Resarch II* 32:217-245.

Craig, P.C. 1987a. Forage fishes in the shallow waters of the north Aleutian shelf. In: Forage fishes of the southeastern Bering Sea: Proceedings of a conference; [dates of meeting unknown]; [location unknown]. OCS Study MMS 87-0017. [Place of publication unknown]: [publisher unknown]: 49-54.

Currie, R.I. 1963. The Incean Ocean Standard Net. Deep Sea Research 10(1-2), p.27-32.

Daly, K. L. and Macaulay, M. C. 1988. Abundance and distribution of krill in the ice edge zone of the Weddell Sea, austral spring 1983. *Deep-Sea Research* 35:21-41.

de Bernardi, Riccardo de. 1984. Methods for the estimation of zooplankton abundance. In JA Drowning & FH Rigler (Eds), A Manual on Methods for the Assessment of Secondary Productivity in Fresh Waters. IBP Handbook 17. 2nd ed. Blackwell, Oxford. Pp. 59-86.

Dolphin, W.F. 1987. Prey densities of humpback whales, Megaptera novaengliae. Experientia 43:468-471.

Falkenhaug, T., K.S. Tande, T. Semenova. 1997. Diel, seasonal, and ontogenetic variations in the vertical distributions of four marine copepods. *Marine Ecology Progress Series* 149:105-119.

Fiedler, P.C., S.B. Reilly, R.P. Hewitt, D. Demer, V.A. Philbrick, S. Smith, W. Armstrong, D.A. Croll, B.R. Tershy, B.R. Mate. 1998. Blue whale habitat and prey in the California Channel Islands. *Deep-Sea research II* 45:1781-1801.

Field, L.J. 1988. Pacific sand lance, Ammodytes hexapterus, with notes on related Ammodytes species. In: Wilimovsky, N.J.; Incze, L.S.; Westrheim, S.J., eds. Species synopses, life histories of selected fish and shellfish of the northeast Pacific and Bering Sea. [Place of publication unknown]: [publisher unknown]: 15-33. Available from: Washington Sea Grant Program, 3716 Brooklyn Ave. NE, Seattle, WA 98105.

Fisheries and Oceans Canada. 2010. Recovery Strategy for the North Pacific Humpback Whale (*Megaptera novaeangliae*) in Canada [DRAFT]. *Species at Risk Act* Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa. x + 51 pp. Fleminger, A., and R.I. Clutter. 1965. Avoidance of towed nets by zooplankton. *Limnology & Oceanography* 10:96-104.

Fleminger, A., R.I. Clutter. 1965. Avoidance of towed nets by zooplankton. Limnology and Oceanography 10: 96-104.

Flinn, Rowenna, A.W. Trites, E.J. Gregr. 2002. Diets of fin, sei, and sperm whales in British Columbia: an analysis of commercial whaling records, 1963-1967. *Marine Mammal Science* 18(3):663-679.

Ford, J.K.B., A.L. Rambeau, R.M. Abernethy, M.D. Boodaards, L.M. Nichol, and L.D. Spaven. 2009. An assessment of the potential for recovery of humpback whales off the Pacific Coast of Canada. Canadian Science Advisory Secretariat Research Document 2009/015.

Ford, JKB, G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, R.S. Palm, K.C. Balcomb III. 1998. Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology, 76(8): 1456-1471.

Foy, R.J., B.L. Norcross. 1998. Spatial and temporal differences in the diet of juvenile Pacific herring (Clupea pallasi) in Prince William Sound, Alaska. In Juvenile Herring Growth and Habitats: Exxon Valdez Oil Spill Restoration Project Annual Report.

Hargreaves PM, Herring PJ (1992) The response of decapod and mysid crustaceans to artificially lighted trawls. J Mar Biol Assoc. UK 72:621–631

Harris, R.P., P.H. Wiebe, J. Lenz, H.R. Skjoldal, M. Huntley, eds. 2000. ICES Zooplankton Methodology Manual. Academic Press: London.

Harrison, P., J. Fulton, F. Taylor, and T. Parsons. 1983. Review of the biological oceanography of the Strait of Georgia: Pelagic environment. *Canadian Journal of Fisheries and Aquatic Science* 40: 1064-1094.

Healey, M. C. 1980 The ecology of juvenile salmon in Georgia Strait, British Columbia. In *Salmonid Ecosystems of the North Pacific* (McNeil, W. J. & Hinsworth, D. C., eds). Oregon State University Press, Corvallis. pp. 203-229.

Heron, A.C. 1982. A vertical free fall plankton net with no mouth obstructions. Limnology and Oceanography 27(3):380-383.

Isaacs, J.D. 1965. Larval sardine and anchovy interrelationships. California Cooperative Oceanic Fisheries Invesitgations Report 10: 102-140.

Jerde, CW. 1967. A comparison of euphausiid shrimp collections made with a micronekton net and a one metre plankton net. Pacif. Sci. 21:178-181.

Johnson, T.B. and M. Terazaki. 2003. Species composition and depth distribution of chaetognaths in a Kuroshio warm-core ring and Oyashio water. Journal of Plankton Research 25(10): 1279-1289.

Kawamura, A. 1980. A review of food of balaenopterid whales. Scientific Report of the Whales Research Institute 32:155-198.

Kawamura, A. 1982. Food habits and prey distributions of three rorqual species in the North Pacific Ocean. Scientific Report of the Whales Research Institute 3$:59-91.

Krieger, K.J., and B.L.Wing. 1985. Location and assessment of humpback whale forage in southeastern Alaska with sonar echo sounding. Unpublished report, Auke Bay Laboratory, NOAA. National Marine Fisheries Service, Auke Bay, AK. 66pp.

Laval, P.H. 1974. Un modele mathematique de l'evitement d'un filet a plankton, son application pratique, et sa verification indirecte en recourant au parasitisme de l'amphipode hyperide Vibilia armata Bovallius. *Journal of Experimental Marine Biology and Ecology* 14:57-87.

Lorz, H.V., & W.G. Pearcy. 1975. Distribution of hyperiid amphipods off the Oregon coast. J. Fisheries Research Board of Canada 32: 1442-1447.

Mackas, D.L. & E.P. Anderson. 1986. Small-scale zooplankton community variability in a northern British Columbian fjord system. *Estuarine, Coastal, and Shelf Science* 22:115-142.

Mackas, D.L. and K.O. Coyle. 2005. Shelf-offshore exchange processes, and their effects on mesozooplankton biomass and community composition patterns in the northeast Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography* 52(5-6): 707-725.

Mackas, D.L., 1992. Seasonal cycle of zooplankton off southwestern British Columbia. *Canadian Journal of Fisheries and Aquatic Science* 49: 903–921.

Mackas, D.L., and A. Tsuda. 1999. Mesozooplankton in the eastern and western subarctic Pacific: Community structure, seasonal life histories, and interannual variability. *Progress in Oceanography* 43:335-363.

Mackas, D.L., R. Kieser, M. Saunders, D.R. Yelland, R.M. Brown, and D.F. Moore. 1997. Aggregation of euphausiids and Pacific hake (Merluccius productus) along the outer continental shelf off Vancouver Island. *Can. J. Fish. Aquat. Sci*. 54: 2080–2096.

Mackas, D.L., R.E. Thomson, and M. Galbraith. 2000. Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. *Canadian Journal of Fisheries Aquatic Sciences* 58:685-702.

Mackas, David L., & M.D. Galbraith. 2002. Zooplankton Distribution and Dynamics in a North Pacific Eddy of Coastal Origin: I. Transport and Loss of Continental Margin Species. *Journal of Oceanography* 58:725-738.

Mackas, D.L., S. Batten, M. Trudel. 2007. Effects on zooplankton of a warmer ocean: recent evidence from the northeast Pacific. Progress in Oceanography 75: 223-252.

McFarlane, G.A., MacDougall, L., Schweigert, J., Hrabok, C. 2005. Distribution and ecology of Pacific sardines (Sardinops sagax) off British Columbia, CA. CalCOFI Report, Vol. 46.

McGowan, J.A., and V.J. Fraundorf. 1966. The relationship between size of net used and estimates of zooplankton diversity. *Limnology and Oceanography* 11:456-469.

Miller, C.B., B.W. Frost, H.P. Bathelder, M.J. Clemons, R.E. Conway. 1984. Life histories of large, grazing copepods in a subarctic ocean gyre: Neocalanus plumchrus, Neocalanus cristatus, and Eucalanus bungii in the Northeast Pacific. Progress in Oceangraphy 13: 201-243.

Miller, C.B., M.J. Clemons. 1988. Revised life history analysis for large grazing copepods in the subarctic Pacific ocean. Progress in Oceanography 20: 293-313.

Miller, C.B., J. Fulton, B.W. Frost. 1991. Size variation of Neocalanus plumchrus and Neocalanus flemingeri in a 20-yr sample series from the Gulf of Alaska.

Nemoto, T. 1957. Foods of baleen whales in the northern Pacific. Scientific report of the Whales Research Institute 12:33-89.

Nemoto, T. 1959. Food of baleen whales with reference to whale movements. Scientific Report of the Whales Research Institute 14:149-290.

Nemoto,T. and T. Kasuya. 1965. Foods of baleen whales in the Gulf of Alaska of the North Pacific. Scientific Report of the Whales Research Institute 19:45-51.

O'Connell, M.; Fives, J.M. 1995. The biology of the lesser sand-eel Ammodytes tobianus l. In the Galway Bay area. Biology and Environment. 95b(2): 87-98.

Ohman, M.D., P.E. Smith. 1995. A comparison of zooplankton sampling methods in the CalCOFI time series. CalCOFI Report Vol. 36.

Ohman, M. 2013. Zooplankton. Crustacean field collection and preservation techniques. DeGrave, Sammy, and Joel Martin, eds. Oxford University Press.

Osgood, K.E., and B.W. Frost. 1994. Comparative life histories of three species of planktonic calanoid copepods in Dabob Bay, Washington. *Marine Biology* 118: 627-636.

Pankhurst, R.C., D.W. Holder. 1952. Wind tunnel technique. London, Pitman.

Pearcy, W.G. 1983. Quantitative assessment of the vertical distribution of micronektonic fishes with opening/closing midwater trawls. Biological Oceanography 2: 289-310.

Peterson, W.T. 1979. Life history and ecology of Calanus marshallae Forst in the Oregon Upwelling Zone. Dissertation at Oregon State University.

Prakash, A. 1962. Seasonal changes in feeding of coho and spring (Chinook) salmon in southern British Columbian waters. J. Fish. Res. Board. Can. 19:851-866.

Pritchard, A.L., and A.L. Tester. 1944. Food of spring and coho salmon in British Columbia. Bull. Fish. Res. Board Can. 65:23p.

Robards, M.D., M.F. Wilson, R.H. Armstrong, J.F. Piatt. 1999. Sand Lance: a review of biology and predator relations and annotaded bibliography. Res. Pap. PNW-RP-521. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 327 p.

Rogers, D.E.; Rabin, D.J.; Rogers, B.J. [and others]. 1979. Seasonal composition and food web relationships of marine organisms in the nearshore zone of Kodiak Island including icthyoplankton, meroplankton (shellfish), zooplankton, and fish. [Seattle, WA]: University of Washington, Fisheries Research Institute, final report FRI-UW-7925: 291 p.

Schulenberger, E. 1978. Vertical distributions, diurnal migrations, and sampling problems of hyperiid amphipods in the North Pacific central gyre. Deep-Sea Research 25: 605-623.

Scott, J.S. 1973. Food and inferred feeding behavior of northern sand lance (Ammodytes dubius). Journal of theFisheries Research Board of Canada. 30: 451-454.

Shaw, W., and Robinson, C.L.K. 1998. Night versus day abundance estimates of zooplankton at two coastal stations in British Columbia, Canada. Mar. Ecol. Prog. Ser. 175: 143–153.

Smith, P.E., R.I. Clutter. 1965. Hydrodynamics of flow and collection in plankton nets. Ocean science and ocean engineering 1: p.515 (abstract).

Smith, P.E., R.C. Counts, and R.I. Cutter. 1968. Changes in filtering efficiency of plankton nets due to clogging under tow. J. Cons. int. Explor. Mer 32(2):232-248.

Swinney GN, Clarke MR, Maddock L (1986) Influence of an electric light on the capture of oceanic deep-sea fish in Biscay. J Mar Biol Assoc UK 66:483–496

Tanasichuk, R. W. 1998. Interannual variations in the population biology and productivity of *Thysanoessa spinifera* in Barkley Sound, Canada, with special reference to the 1992 and 1993 warm ocean years. Marine Ecology Progress Series 173: 181-195.

Terazaki, M., C.B. Miller. 1986. Life history and vertical distribution of pelagic chaetognaths at Ocean Station P in the subarctic Pacific. Deep-Sea Research 33: 323-337.

Tomilin, A.G. 1957. Kitoobraznye [Cetacea]. Vol. 9 of Sveri SSSR I Prilezhaschchikh stran [Mammals of the U.S.S.R. and Adjacent Countries]. Izedatel'stvo Akademi Nauk SSSR, Moscow. 756 pp. (Translated by Israel Program for Scientific Translations, 1967, 717 pp., NTIS No. TT 65-50086.)

Tranter, DJ. 1963. Comparison of zooplankton biomass determinations by Indian Ocean Standard net, Juday net and Clarke-Bumpus sampler. Nature 4886: 1179.

Tranter, D.J., A.C. Heron 1967. Experiments on filtration in p[lankton nets. Australian Journal of marine Freshwater Research 18:89-111.

Tranter, D.J., Fraser, J.H., eds. 1968. Zooplankton Sampling. Monographs on Oceanographic Methodology 2. Paris. UNESCO Press.

Tranter, D.J., P.E. Smith. 1968. Filtration Performance. In "Monographs on oceanographic methodology 2: Zooplankton Sampling", UNESCO, Switzerland.

Trevorrow, Mark V., D.L. Mackas, M.C. Benfield. 2005. Comparison of multifrequency acoustic and in situ measurements of zooplankton abundances in Knight Inlet, British Columbia. *Journal of the Acoustical Society of America* 117 (6):3574-3588.

Trumble, R.J. 1973. Distribution, relative abundance, and general biology of selected underutilized fishery resources of the eastern north Pacific Ocean. Seattle, WA: University of Washington. 178 p. M.S. thesis.

Tsuda, A., H. Saito, H. Kasai. 1999. Life histories of Neocalanus flemingeri and Neocalanus plumhcrus (Calanoida: Copepoda) in the western subarctic Pacific. Marine Biology 135: 533-544.

Tsuda, A., H. Saito, H. Kasai. 2001. Geographical variation of body size of Neocalanus cristatus, N. plumchrus, and N. flemingeri in the Subarctic Pacific and its marginal seas: implications for the origin of large form of N. flemingeri in the Oyashio area. Progress in Oceanography 57:341-352.

Weibe, P.H., S.H. Boyd, B.M. Davis, and J.L. Cox. 1982. Avoidance of towed nets by the euphausiid Nematoscelis megalops. *Fishery Bulletin* 80(1).

Wiebe, P.C, and M.H. Benfield. 2003. From the Hensen net toward four-dimensional biological oceanography. Progress in Oceanography 56(1):7-136.

Yamada, Y., T. Ikeda, A. Tsuda. 2004. Comparative life history study on sympatric hyperiid amphipods (Themisto pacifica and T. japonica) in the Oyashio region western North Pacific. Marine Biology 145: 515-527.

Figures & Tables

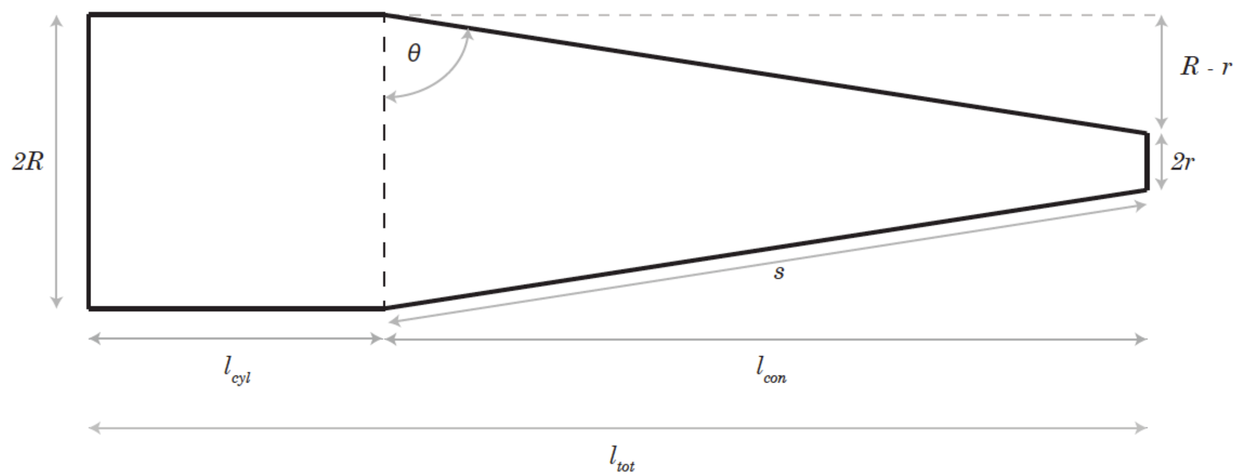


Figure 1. The idealized cyl-cone net model used in this paper.

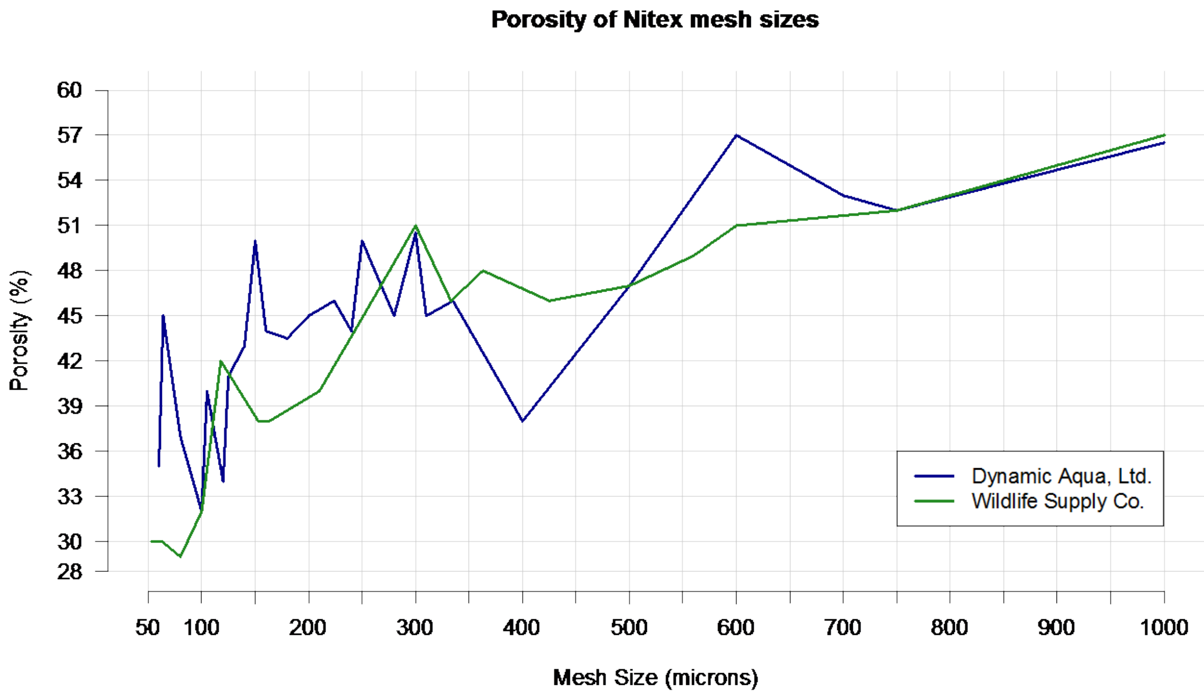


Figure 2. The porosity of Nitex mesh at different apertures, from two distributors. Once you decide upon the mesh size needed to retain your target organisms, use this figure to determine what the porosity of your net will be. Because monofilament of different thicknesses can be used to manufacture Nitex of the same mesh size, porosity is not neatly correlated to aperture.

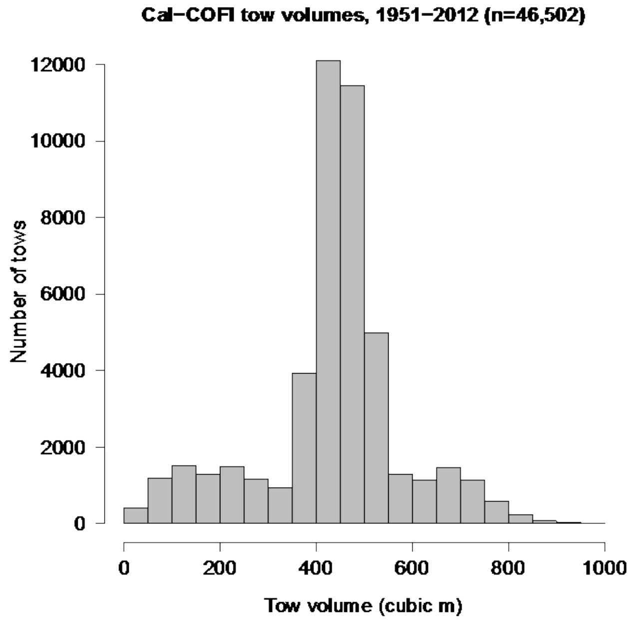


Figure 3. Histogram of the volumes (m^3) of individual tows conducted by the CalCOFI study between 1951 and 2012 (n=46,502, mean=437.7 m^3, sd=147.5 m^3).

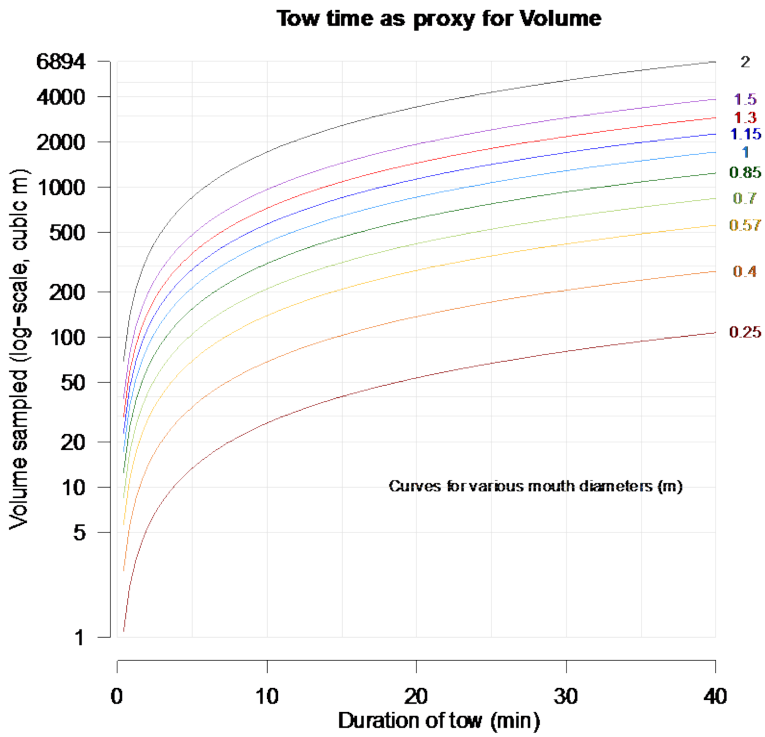
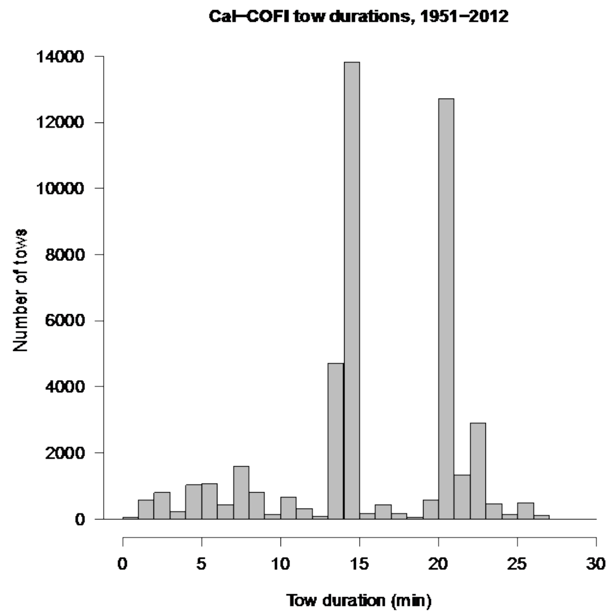


Figure 4. The time duration of a tow can be a useful proxy for the volume sampled, as long as diameter of the net mouth, speed over water and the initial filtration efficiency of your net is known. Above, we assume 1 m/s and 85%, respectively. See Net Model Parameters for justification. Each colored line is the relationship for a certain diameter (given in meters to the right of each line).

a)



b)

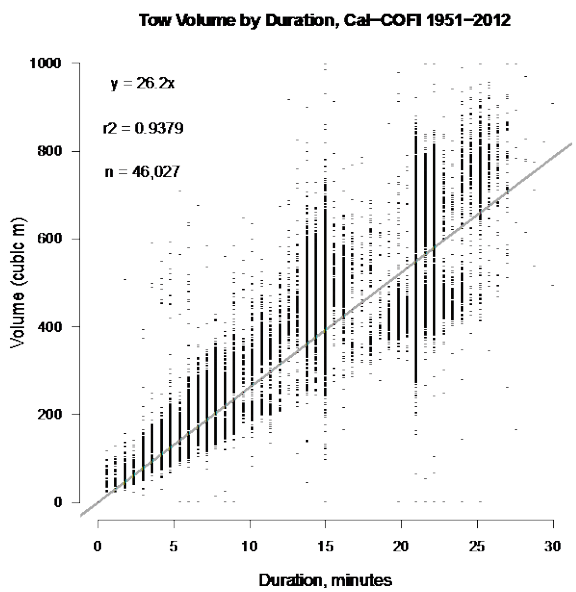


Figure 5. a) Histogram of tow durations (in minutes) from the CalCOFI log, 1951-2012 (n=46,027). The two peaks at 14 and 21 minutes may represent differing protocols for different equipment. b) Sample volume (m^3) as a function of tow duration (minutes) from the CalCOFI log, 1951-2012. There is a tight correlation between volume sampled and the time duration of a tow, as long as the net design provides a high sustained filtration efficiency and clogging does not set in before the end of the tow. The two modes at 15 and 20 minutes may correspond to the two different types of equipment used during this time period.

a) b)

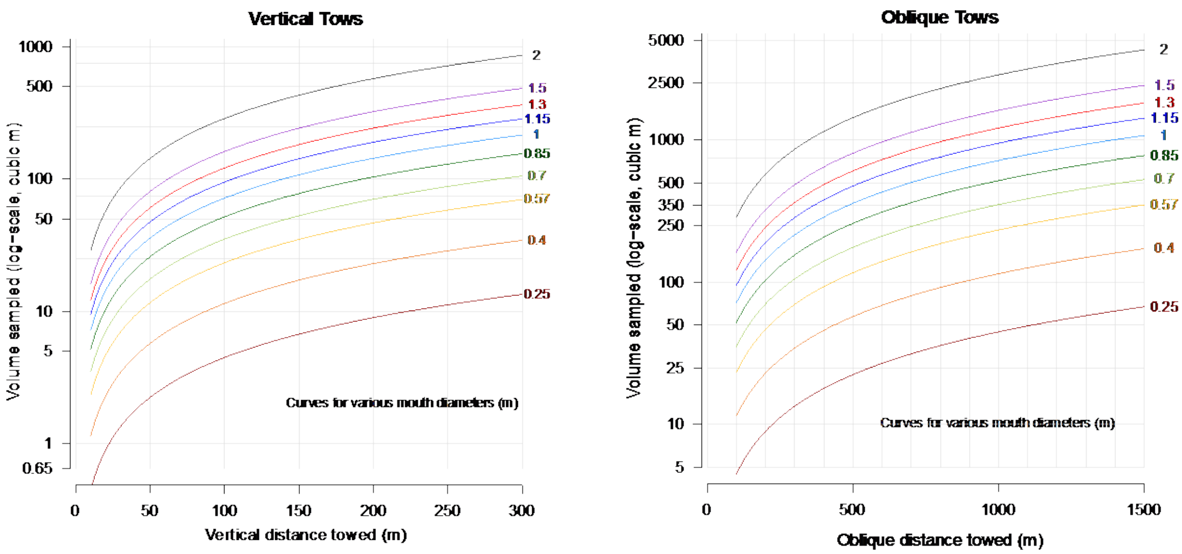


Figure 6. The sample volume of a tow as a function of distance towed for a range of net diameters. a) Distances typical of vertical tows; b) distances typical of oblique tows. An initial filtration efficiency of 91.4% is assumed.

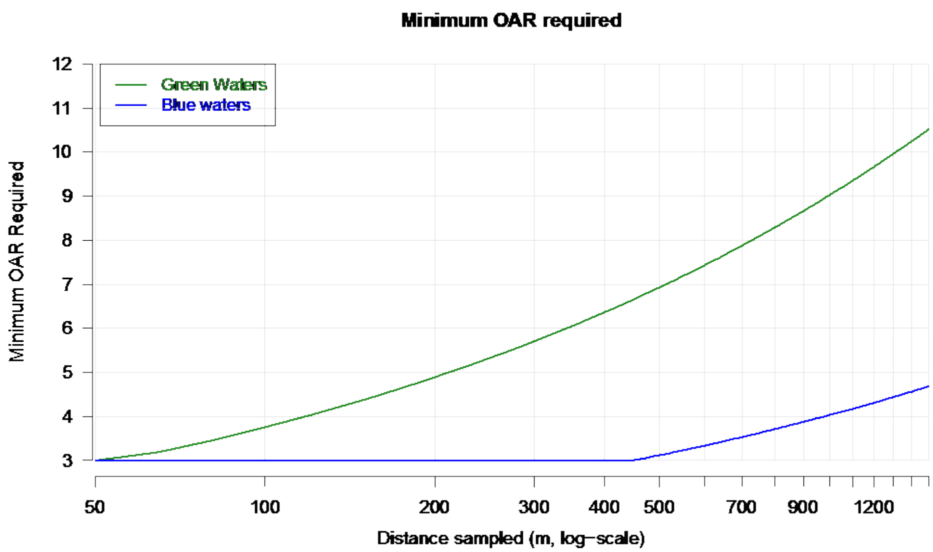


Figure 7. The minimum OAR needed in order for a net to sample a given distance without losing efficiency to clogging, adapted from Tranter & Smith (1968). For a given distance, a net towed through “Green waters” (green line) requires a higher OAR than a net towed through blue water. The minimum OAR of 3:1 (Tranter & Smith 1968) is enforced for distances that don’t call for a higher ratio.

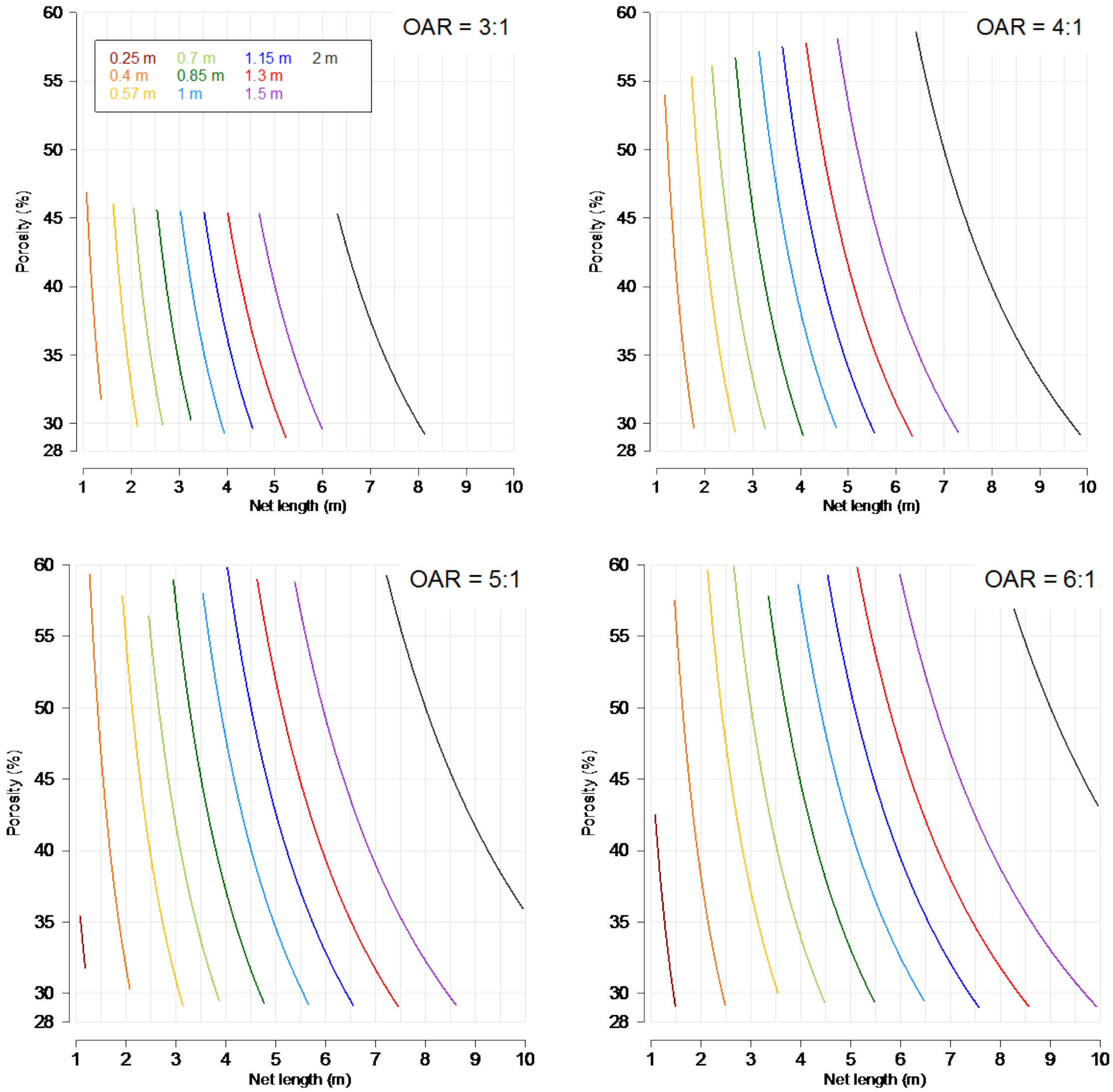


Figure 8. The relationship between net diameter (colored lines), porosity (y-axis), and the overall length (x-axis) needed to achieve a given OAR (panels). This assumes a 7.5cm-diameter cod end, and a side angle of 81.33°. Once the required OAR for your net is known, reference the frame associated with that OAR value. The point of intersection between the target diameter and porosity for your study indicates the necessary length for your net.

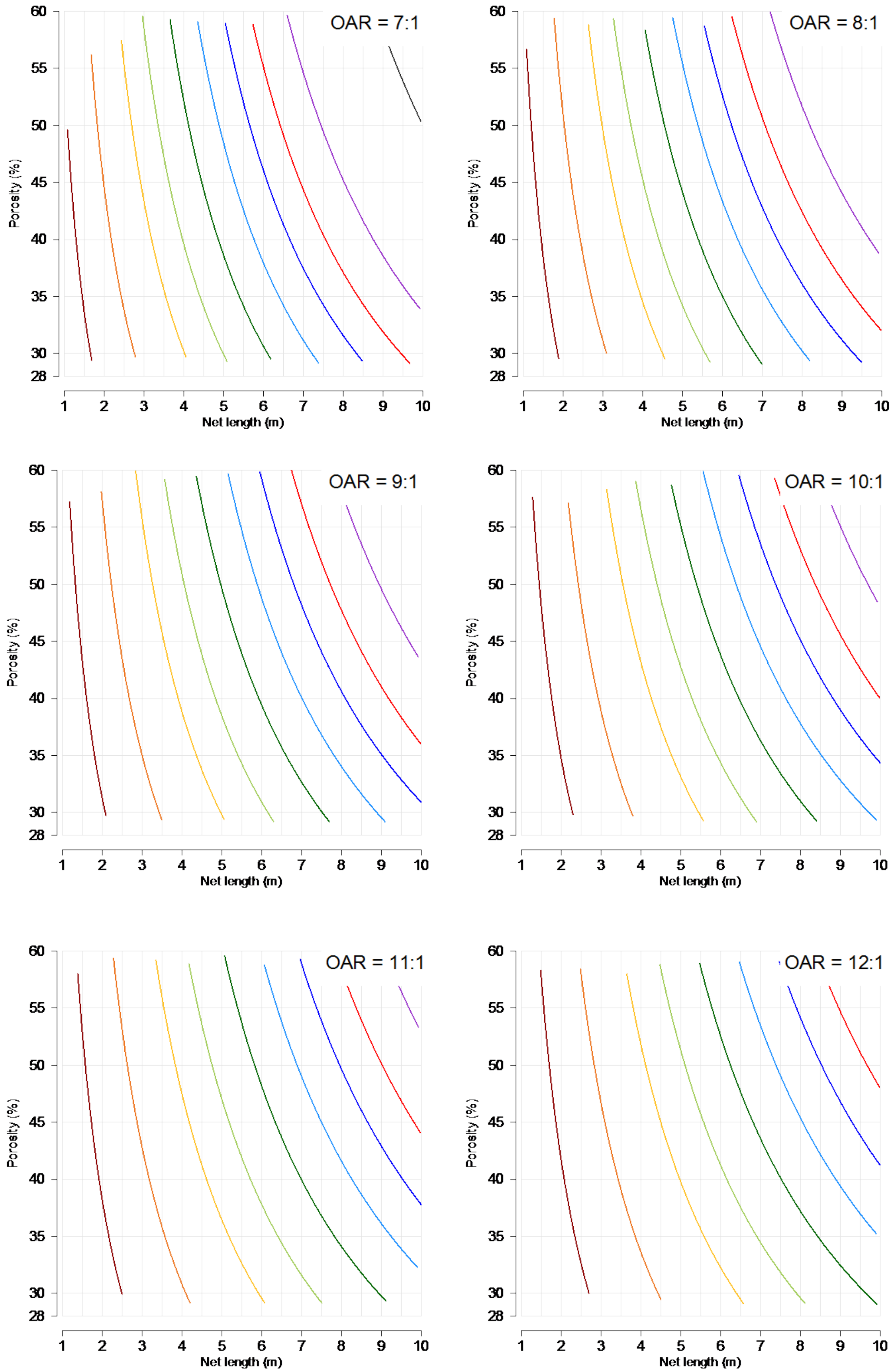


Figure 8. (continued).

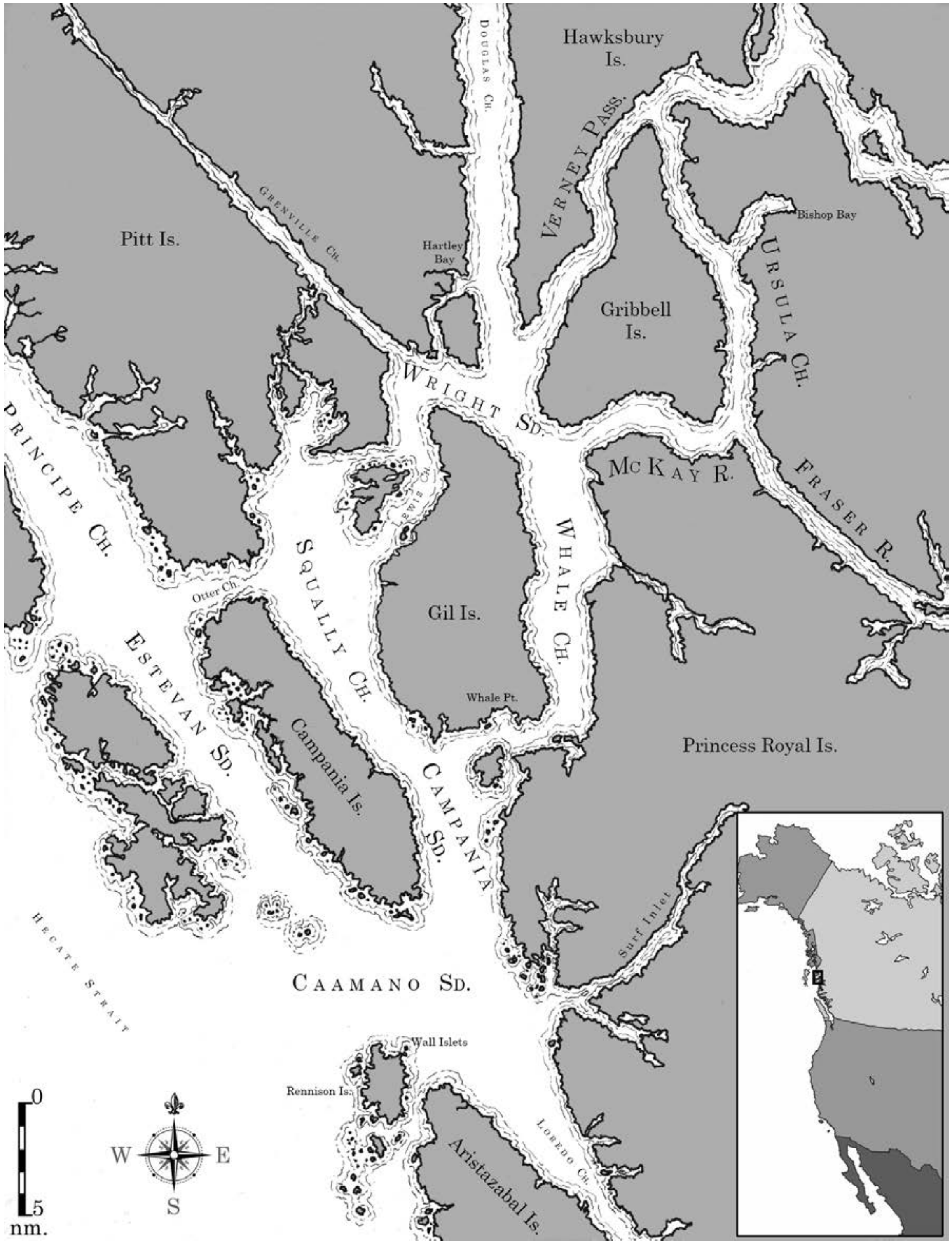


Figure 9. Case study area: the Kitimat Fjord System of northern British Columbia, Canada.

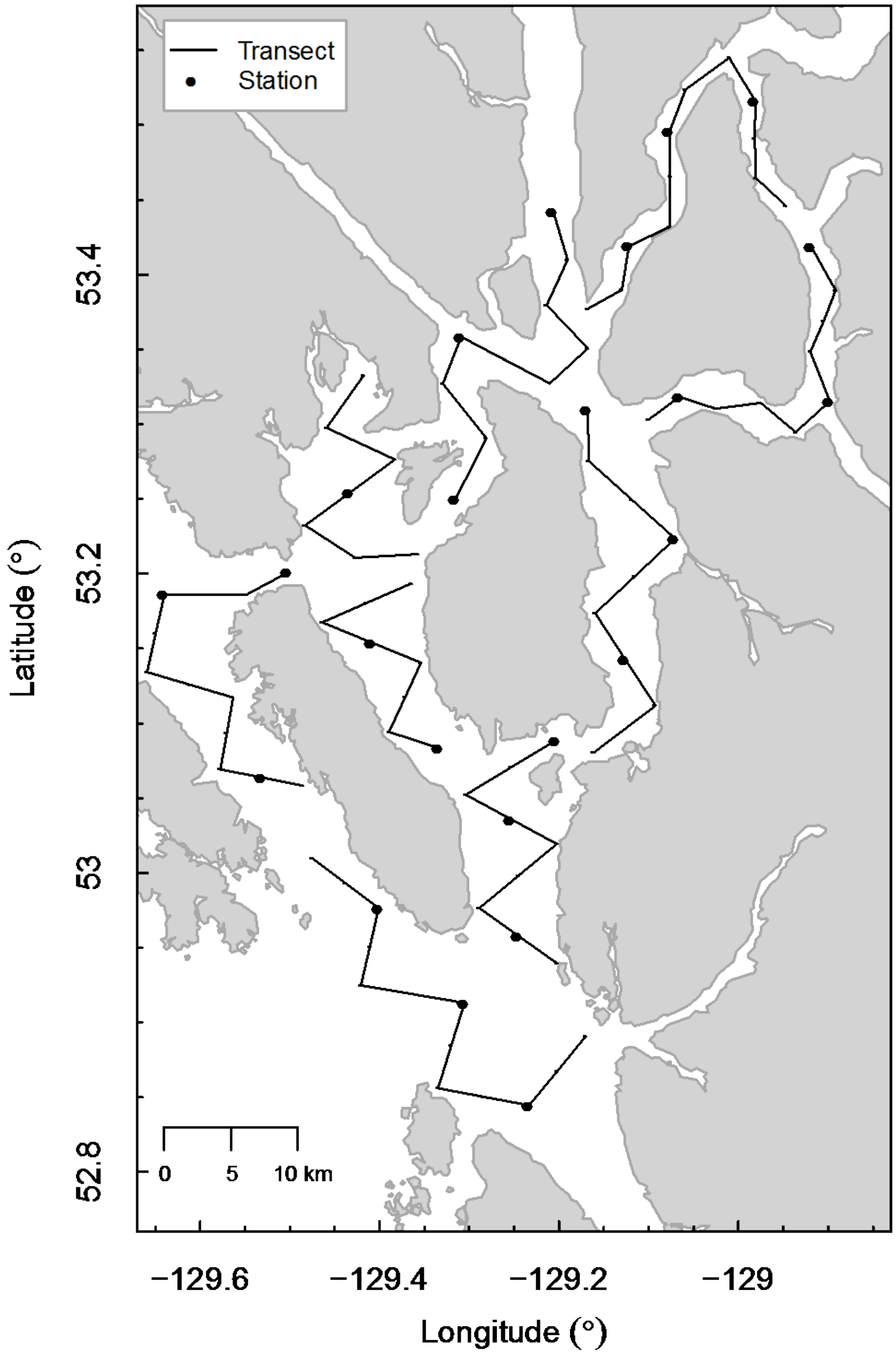


Figure 10. 2014 Study plan, with the ecological sampling stations (n=24) for this study. Stations are distributed throughout the intracoastal zone to allow for patterns to be resolved over both space and time. Stations that will be covered in the same day are connected by black transect lines, such that all 29 stations will be visited every two weeks.

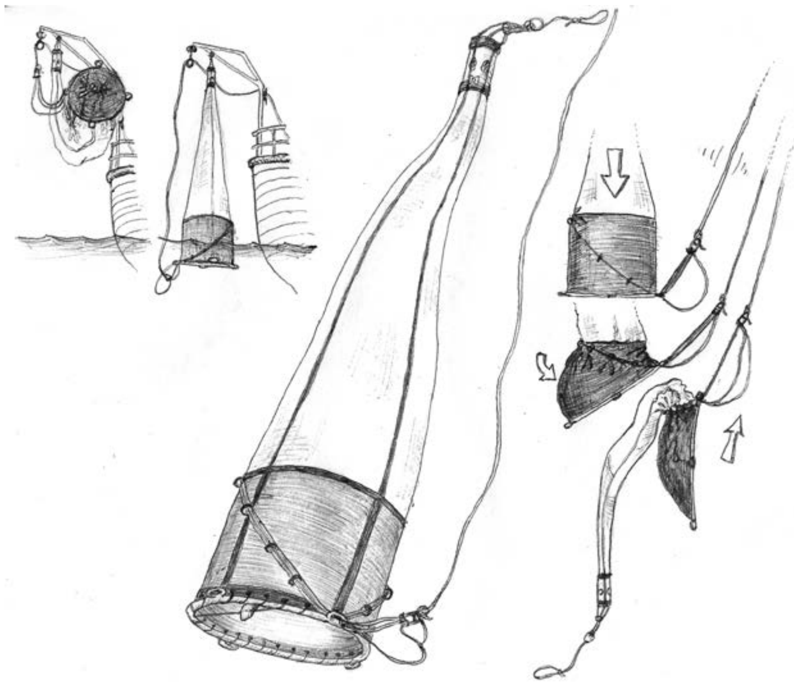


Figure 11. The “Heron-Bangarang” sampler in various stages of storage and deployment. This is the final net design for the case study, adapted from Heron (1982). 0.7m-diameter, solid ¾” 316 stainless steel ring with welded eye bolts;; Black Dacron cylindrical collar (.7m length) with chokeline led through caribeners from fore to aft borders of the collar; 2.7m conical section with 333 micron mesh; 7.5cm cod-end.

Figure 12. Realization of the “Heron-Bangarang” design in Fig. 11. Author (2.02m height) for scale.

Table 1. Abbreviations and parameters used in this guide.

Symbol	Description
"Cyl-cone"	A cylinder-cone net (see Fig. 1)
IFE	Initial filtration efficiency
SFE	Sustained filtration efficiency
OAR	Open-Area Ratio of the net (equiv. "R" in Tranter & Smith (1968) et al.)
MOAR	Minimum Open-Area Ratio.
a_{cyl}	Lateral surface area of the cylindrical section of the net
a_{con}	Lateral surface area of the tapered cylindrical ("conical") section of net
a	Total filtering area of a net
A	Area of net mouth
β	Porosity of a net
R	Radius of the net mouth
r	Radius of the cod-end (given as 3.5cm)
l_{cyl}	Length of the cylindrical section of net
l_{cone}	Length of the conical section of net
l_{total}	Overall length of the entire net
s	Length of the tapered side of the net's conical section
θ	The side angle (given as 75); angle between the tapered surface of conical section and a plane parallel to the net mouth

Table 2. A selection of zooplankton field studies (n=23) relevant to our case study area or the taxa of interest, or both. Operating range is defined as the distance of the longest tow reported in the paper. Studies that used multiple nets with different configurations have a row for each net type used.

Study	Target Group(s)	Region	Equipment	Orientation	Operating Range (m)	Mesh size (μ)	Diameter (m)
Bollens et al. 1992	*Euphausia pacifica, Thysanoessa spp.*	Dabob Bay, WA	Multi-sample	Vertical (stratified)	50 max.	333	1.14
Bollens et al. 1992	*E. pacifica, T. spp.*	Dabob Bay, WA	Tucker Trawl	Oblique (stratified)	193 max.	500	1.14
Coyle & Pincuk 2005, 2003	Large zooplankton, micronekton	Gulf of Alaska	MOCNESS	Oblique (stratified)	100	500	1.14
Coyle & Pincuk 2005, 2003	Small zooplankton: *Neocalanus*, *Metridia spp.*, etc.	Gulf of Alaska	Cal-Vertical EggTow, CALVET	Vertical (integrated)	100	150	0.25
Falkenhaug et al. 1997	Copepods: *Calanus*, *Metridia*, *Chiridius*	Norwegian fjord	MOCNESS	Oblique (stratified)	360	180	1
Fiedler et al. 1998	Blue whales, *E.* pacifica, *T. spinifera*, micronekton	Channel Islands	2m Isaacs-Kid mid-water trawl	Oblique (integrated)	200	505	2.94
Harris et al. 2000. ICES Manual	Mesozooplankton	Temperate coastal zone	WP-2	Oblique (integrated)	NA	200	0.75
Johnson & Terazaki 2003	Chaetognaths	Kuroshio-Oyashio warm-ring	ORI Vertical Multiple Plankton Sampler	Vertical (stratified)	100	333	0.5
Lorz & Pearcy 1975	Hyperiid amphipods	Oregon coast	Single-net	Both	200	571	1
Mackas & Anderson 1986	Copepods, euphasiids, amphipods, etc	Northern BC	Clark-Bumpus (opening/closing)	Oblique (integrated)	470	390	0.125
Mackas & Galbraith 2002	Copepods, euphausiids; Coastal vs oceanic assemblages	North Pacific gyre	BIONESS	Oblique (stratified)	250	230	0.3
Mackas 1992	Euphausiids, Calanoid Calanoid & cyclopoid copepods, chaetognaths	Juan de Fuca Strait	BONGO	Vertical (integrated)	250	220	NA

Table 2. (Continued).

Study	Target Group(s)	Region	Equipment	Orientation	Operating Range (m)	Mesh size (u)	Diameter (m)
Mackas et al. 2000	Copepods, euphausiids, chaetognaths, salps	W. Vancouver Island	BONGO	Oblique (integrated)	250	230	0.3
Miller & Clemons 1988	*Neocalanus plumchrus* and *flemingeri*	Subarctic Pacific	Miller	Vertical (stratified)	1000	333	0.7
Miller & Clemons 1988	*Neocalanus plumchrus* and *flemingeri*	Subarctic Pacific	Miller	Vertical (stratified)	1000	70	0.7
Miller et al. 1984	*Neocalanus* and *Eucalanus* spp.	North Pacific subpolar gyre	Puget Sound	Vertical (stratified)	2000	73 and 330	0.7
Miller et al. 1991	*Neocalanus plumchrus* and *flemingeri*	Gulf of Alaska	Miller	Vertical (stratified)	1200	351	0.56
Osgood & Frost 1994	*Calanus* and *Metridia* copepods	Dabob Bay	Puget Sound Nets	Vertical (integrated)	175	73	1
Osgood & Frost 1994	*Calanus* and *Metridia* copepods	Dabob Bay	Puget Sound Nets	Vertical (integrated)	185	73	.6 or .4
Peterson 1979	*Calanus marshallae*	Oregon coast	BONGO	Oblique	"Entire water column"	240	0.2
Peterson 1979	*Calanus marshallae*	Oregon coast	WP-2	Oblique	40	120	12.7
Schulenberger 1978	Hyperiid amphipods	N. Pacific gyre	BONGO (opening-closing)	Vertical (stratified)	250	333	0.7
Tanasichuk 1998	Euphausiids	Barkley Sound, Canada	BONGO	Oblique (integrated)	250	330	0.6
Terazaki & Miller 1986	Chaetognaths	Subarctic Pacific	"Puget Sound" (opening-closing)	Vertical (stratified)	1000 max.	333 / 73	0.7
Trevorrow et al 2005	Mesozooplankton (copepods), and macrozooplankton (incl. gelatinous taxa)	Knight Inlet	BIONESS	Oblique (stratified)	500	220	0.25
Tsuda et al. 1999	*Neocalanus plumchrus* and *flemingeri*, stages C2 to C6	Oyashio	BONGO	Oblique	900	333	0.7
Tsuda et al. 2001	*Neocalanus plumchrus* and *flemingeri*	Subarctic Pacific	BONGO	Vertical (integrated)	1000	333	0.7
Tsuda et al. 2001	*Neocalanus plumchrus* and *flemingeri*	Subarctic Pacific	ORI	Oblique (integrated)	1200	1000	1.6
Yamada et al. 2004	Hyperiid amphipods	Oyashio	BONGO	Oblique (integrated)	500 avg., 900 max.	333	0.7
Yamada et al. 2004	Hyperiid amphipods	Oyashio	MTD	Vertical (stratified)	1100 max.	333	0.56

RECENT TECHNICAL MEMORANDUMS

SWFSC Technical Memorandums are accessible online at the SWFSC web site(http://swfsc.noaa.gov). Print copies are available from the National Technical Information Service, 5285 Port Royal Road,, Springfield, VA 22161 (http://www.ntis.gov).