

REVIEW

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Light traps for sampling marine biodiversity

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Abstract

Standardised sampling methods are required to meet the Convention on Biological Diversity Aichi Targets to monitor trends in biodiversity. Currently the animals monitored in the marine environment are predominantly vertebrates and surface plankton, but arthropods (especially benthic crustaceans) make up a third of marine species, provide an important link in the food web and are under sampled. Sampling these animals with light traps on the benthos in structurally complex areas would fill a gap in biological monitoring. A survey of the literature of light-trap designs showed they collected at least 12 phyla of benthic and planktonic animals, and 13 orders of crustaceans. These traps can be deployed anywhere from an hour to overnight and on the seabed or in the water column. They can be low cost, have low environmental impact and be used in complex and fragile habitats otherwise difficult to sample. Environmental factors, such as water movement and turbidity, as well as trap design and method of deployment, may affect catch. Experimental field tests are required to develop the use of light-traps as a standard method for marine biodiversity monitoring, including design, deployment, and replication.

Keywords: Light traps, Biodiversity, Monitoring, Demersal, Plankton, Benthos, Macrofauna, Crustacea, Fish

Background

Methods for monitoring trends in biodiversity are urgently required by the Convention on Biological Diversity's Aichi Targets to help stem the decline of biodiversity worldwide [1]. To facilitate this, Pereira et al. [2] proposed the implementation of Essential Biodiversity Variables. One of these proposed EBVs is to measure species population abundances. This would require, "Counts or presence surveys for groups of species easy to monitor or important for ecosystems, over an extensive network of sites, complemented with incidental data" [2]. These EBVs should be sensitive to change, technically feasible, economically viable and sustainable in time [2–4].

Most current marine sampling is centred on vertebrates that either have commercial importance (i.e., fishes) or intrinsic appeal (i.e., birds and marine mammals) [3]. Although chordates only make up 11% of the oceans known species, they are disproportionately sampled and comprise over 60% of the records in the Ocean

Biogeographic Information System (OBIS) [5]. Arthropods and molluscs on the other hand account for over half of all marine species, but make up only 26% of the OBIS records. One of the notable contributors to invertebrate sampling is the Continuous Plankton Recorder, which has repeatedly collected surface plankton across oceans for over 80 years [6]. However, as its sampling is limited to the surface waters of the open ocean it gathers a rather narrow range of species. While there were 12 phyla identified, over 65% of the species identified were calanoid copepods [7–9]. Many of the wider array of species in the ocean that form the base of the food web are monitored substantially less due to sampling costs and effort. Macrofaunal invertebrates are a key link between primary production and the rest of the food web, providing prey for birds, fish and shellfish [10–14]. They often inhabit structurally complex habitats like reefs, epifaunal turfs, and vegetation which are difficult to sample without damaging the habitat (Table 1). Minimising habitat damage is especially important when sampling protected areas and biogenic habitats [15]. Thus a major component of marine food webs and biodiversity is largely overlooked in monitoring programmes.

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Table 1 Common invertebrate sampling techniques. Adapted from [3]

Method	Organisms collected	Drawback
Benthic core	Animals buried in the sediments	Destructive as habitat is removed in sampling. More mobile animals escape. Time consuming to collect and process samples. Specimens usually damaged during collection
Grab sample		
Dredge	Specimens at and just below surface	
Quadrat scraping	Sessile animals on solid surface	Destructive. Expensive equipment and labour intensive
Suction sampler	Benthic organisms	
Plankton net or pump	Free floating and slow moving organisms	Cannot sample in structurally complex areas. Specimens can be damaged by net. More mobile taxa escape
Visual including photography	Observe larger mobile fauna and sessile and sedentary macrobiota	Mobile macrofauna not sampled
Baited traps	Larger mobile macrofauna	Limited to scavenging species and will attract megafauna that predate smaller species
Artificial substrata	Sessile, sedentary and nestling biota	Have to be left in situ for weeks to months to be colonised
Emergence and sediment traps	Select benthic animals that move up or down in water column	Need to be large to capture sufficient number of animals and/or left in place for days

The light trap's passive sampling, retention of live specimens, and low cost, has made it widely used for sampling insect diversity in terrestrial environments [16]. For example, light traps have been used consistently and extensively for standardized mosquito monitoring since the 1940s [17–19] and for monitoring moths and other species considered as pests [20, 21]. The advantages that light traps bring to terrestrial sampling may also make them useful for monitoring marine invertebrates. Although light traps have been used underwater, a standard trap and methodology has not been developed for monitoring invertebrates. Here we review the use of light-traps in the marine environment, and assess their potential as a standard method for monitoring biodiversity.

Uses

In the marine environment light traps have had a few purposes: to complement plankton tows in collecting organisms that may avoid tows (e.g., late stage larval fishes); to sample organisms with minimal damage for ease of identification and inclusion in reference collections of specimens; to collect live organisms for research (e.g., [22]) and teaching (authors unpublished); and for collection in areas where plankton nets may cause damage to sensitive species (e.g., corals) or be damaged by structurally complex habitats (e.g., rocky reefs) [23]. As passive sampling methods, light traps are useful when multiple locations need to be sampled simultaneously [24]. Light traps were also developed for deploying on salmon farms in an attempt to reduce copepod parasite infestations but were not commercially successful [25–28].

Most commonly, light traps have been used in coral reef environments [23] as their static nature gives them an

advantage over towed equipment in these sensitive areas. However, their uses have also been explored in temperate waters [29–31], tropical mangroves [32], and Antarctic ice flows [33]. Although most often used to collect larval fishes (over 100 families and 324 species, Additional file 1: Table S1), they have also collected invertebrates from over 12 phyla (Table 2). Crustaceans comprise the greatest richness of invertebrate species collected (Table 3) with at least 128 different species reported (Additional file 1: Table S2). Light traps have also been used for monitoring crab and lobster recruitment [30, 34, 35].

Design and construction

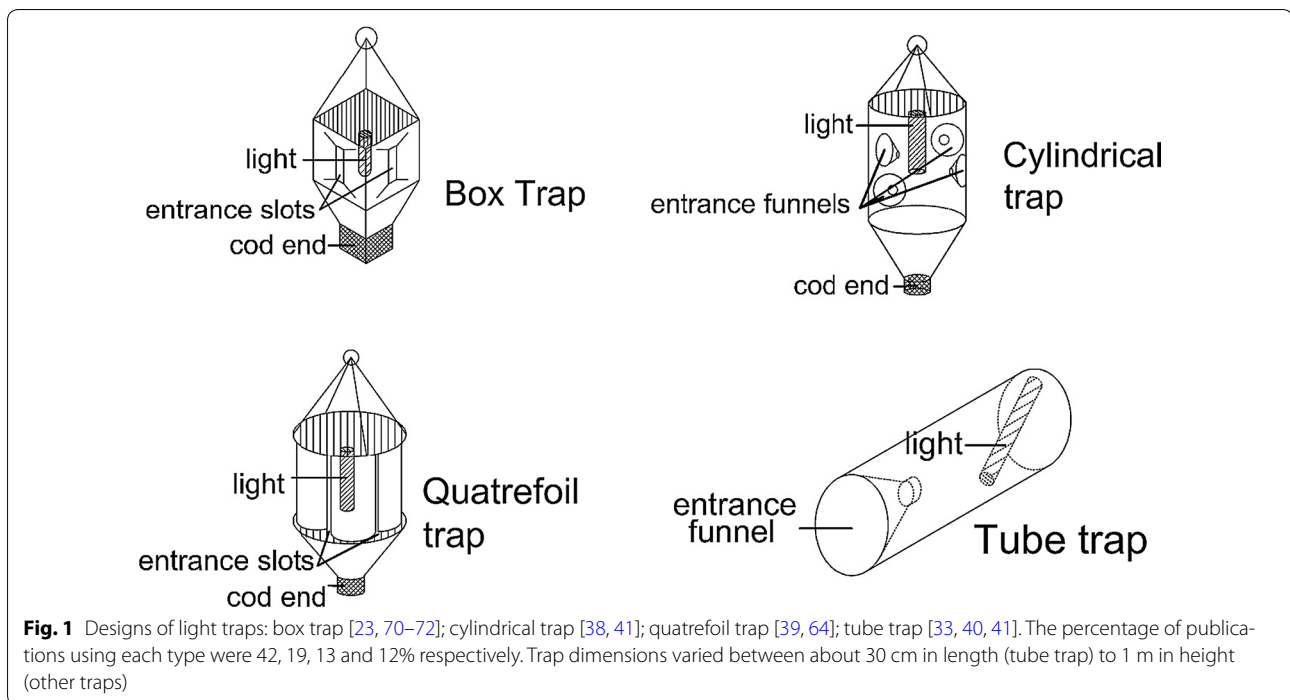
In 94 papers reviewed we found there were 49 original designs, with many more including modifications of previous designs. Designs ranged from very basic and inexpensive 1–2 L tube (bottle) traps with funnel entrances to a 240 L box trap with pulsing lights (Fig. 1). Larger traps are more difficult to handle and can be more expensive to construct. The only comparison between trap sizes found the smaller (box) traps had a similar or greater catch of fish and invertebrates than the larger [36]. The most common designs were a form of box trap with tapered entrances on four sides. They can have adjustable entrance slots [37], multiple chambers [23, 24], and a cod-end for catching and filtering the organisms as the trap is removed. Flat sided traps may suffer from inefficiencies in capturing organisms as some animals that are attracted to the light may never find the entrances [38]. The quatrefoil trap was designed to mitigate this problem [39]. Its shape resembles a four lobed cloverleaf with each side leading to an entrance that directs attracted animals into the trap. One study found the quatrefoil trap to collect significantly more larval fish than cylindrical and box

Table 2 Higher taxa reported to have been collected in light traps in the marine environment. Where available, the number of species identified is given. n/a = not available as only identified to phylum level. See Additional file 1: Tables S1 and S2 for detailed list of taxa

Phylum	Number species	References
Annelida, Polychaeta	1	Zismann [94], Jones [46], Fincham [55], Sale et al. [88], Smith et al. [90], Tranter et al. [93], Kawaguchi et al. [33], Meekan et al. [36, 38], Carleton et al. [75], Granek and Frasier [32], Mwaluma et al. [40], Tor et al. [92]
Arthropoda	128	Zismann [94], Jones [46], Fincham [55], Smith et al. [90], Tranter et al. [93], Kawaguchi et al. [33], Holmes and Jeal [82], Song and Yun [91], Meekan et al. [36, 38], Carleton et al. [75], Hovda and Fosshagen [54], Roegner et al. [30], Granek and Frasier [32], Øresland [34], Herter and Eckert [81], Porter et al. [87], Mwaluma et al. [40], Michel et al. [43], Tor et al. [92], Chang [76], Kim et al. [85], Sigurdsson et al. [89], Costello et al. [41]
Chaetognatha	1	Jones [46], Fincham [55], Smith et al. [90], Tranter et al. [93], Carleton et al. [75], Granek and Frasier [32], Costello et al. [41]
Cnidaria	3 classes	Carleton et al. [75], Mwaluma et al. [40]
Chordata	320	Carleton et al. [75] and Additional file 1: Table S1
Ctenophora	1	Carleton et al. [75]
Echinodermata	n/a	Carleton et al. [75]
Hemichordata	n/a	Carleton et al. [75]
Mollusca	6	Zismann [94], Fincham [55], Thorrold [60], Carleton et al. [75], Jackson et al. [83], Mwaluma et al. [40], Tor et al. [92], Costello et al. [41]
Nematoda	n/a	Zismann [94], Costello et al. [41]
Phoronida	n/a	Carleton et al. [75]
Platyhelminthes	One class	Carleton et al. [75], Costello et al. [41]
Tunicata	1	Carleton et al. [75]

Table 3 The higher taxa and number of species of marine crustaceans that have been collected in light traps

Class or order	Number of species	References
Amphipoda	27	Zismann [94], Jones [46], Fincham [55], Smith et al. [90], Tranter et al. [93], Kawaguchi et al. [33], Holmes and Jeal [82], Meekan et al. [36, 38], Carleton et al. [75], Granek and Frasier [32], Mwaluma et al. [40], Michel et al. [43], Tor et al. [92], Kim et al. [85], Sigurdsson et al. [89], Costello et al. [41]
Cumacea	24	Hale [50, 80], Zismann [94], Fincham [55], Smith et al. [90], Tranter et al. [93], Kawaguchi et al. [33], Carleton et al. [75], Meekan et al. [36], Granek and Frasier [32], Tor et al. [92], Costello et al. [41]
Decapoda	17	Zismann [94], Jones [46], Fincham [55], Smith et al. [90], Tranter et al. [93], Meekan et al. [38], Carleton et al. [75], Roegner et al. [30], Granek and Frasier [32], Øresland [34], Herter and Eckert [81], Porter et al. [87], Mwaluma et al. [40], Tor et al. [92], Sigurdsson et al. [89], Costello et al. [41]
Euphausiacea	5	Jones [46], Fincham [55], Kawaguchi et al. [33], Meekan et al. [36, 38], Carleton et al. [75], Granek and Frasier [32], Tor et al. [92], Sigurdsson et al. [89], Costello et al. [41]
Isopoda	2	Zismann [94], Jones [46], Fincham [55], Tranter et al. [93], Kawaguchi et al. [33], Holmes and Jeal [82], Meekan et al. [36, 38], Carleton et al. [75], Granek and Frasier [32], Tor et al. [92], Sigurdsson et al. [89], Costello et al. [41]
Leptostraca	1	Tor et al. [92]
Mysida	4	Zismann [94], Jones [46], Fincham [55], Smith et al. [90], Kawaguchi et al. [33], Meekan et al. [36, 38], Carleton et al. [75], Granek and Frasier [32], Tor et al. [92], Sigurdsson et al. [89], Costello et al. [41]
Stomatopoda	To phylum only	Zismann [94], Fincham [55], Meekan et al. [38], Carleton et al. [75], Granek and Frasier [32], Mwaluma et al. [40], Tor et al. [92], Costello et al. [41]
Tanaidacea	To phylum only	Zismann [94], Kawaguchi et al. [33], Granek and Frasier [32], Tor et al. [92], Costello et al. [41]
Calanoida Copepoda	29	Jones [46], Smith et al. [90], Tranter et al. [93], Kawaguchi et al. [33], Holmes and Jeal [82], Carleton et al. [75], Hovda and Fosshagen [54], Tor et al. [92], Costello et al. [41]
Other Copepoda	15	Smith et al. [90], Tranter et al. [93], Gotto et al. [78], Kawaguchi et al. [33], Holmes and Jeal [82], Song and Yun [91], Carleton et al. [75], Hovda and Fosshagen [54], Tor et al. [92], Chang [76], Costello et al. [41]
Cirripedia	1	Jones [46], Carleton et al. [75], Granek and Frasier [32], Costello et al. [41]
Ostracoda	4	Zismann [94], Fincham [55], Smith et al. [90], Tranter et al. [93], Holmes and Jeal [82], Carleton et al. [75], Granek and Frasier [32], Mwaluma et al. [40], Tor et al. [92], Costello et al. [41]



traps [40]. Only one study quantified animal escape from traps [38] and this is likely to be the case to some extent for all traps while deployed and during retrieval.

The quatrefoil and larger traps may need to be built in a workshop or purchased commercially. However, many others have also had success with low tech traps made from recycled water bottles [41, 42], jugs [30, 43], buckets [44], plastic bins [29], or simple tubes [34, 45]. Mesh traps, where the principle body of the trap is constructed of netting have also been employed [46–49]. However, animals attempting to enter the trap can clog the outside of the net and impede the transmittance of the light [22].

Type of light

The type of light used within a light trap can vary in colour, intensity and type. Traditionally fluorescent or incandescent bulbs have been used but chemical lights are also very common. The use of LED lights is on the rise and currently appears to be the best option as they are robust, inexpensive, and have low energy requirements (Table 4). The optimum brightness of illumination has not been studied. While Hale [50] observed a greater catch with lights of 26.9 lm m^{-2} than with very bright lights, comparative experiments were not reported. Blue, green and yellow coloured lights appear to have the highest catch rates [51–53] although this may be confounded with the intensity of the lights used. Red lights appear to have the least success. Since longer wavelengths are the

first to be attenuated in water the lack of success with red lights seems likely to be due to a lower distance of illumination.

Biases

Light traps select for photo positive organisms. Since phototaxis can change during development light traps may target some life stages or even sexes more than others [53, 54]. In studying amphipods with light traps, Fincham [55] found that adult male benthic amphipods dominated light trap catches with juvenile and female presence varying throughout the lunar cycle and at times being absent. For larval fishes, light traps tend to catch larger (older) larvae than plankton nets and fewer individuals [29, 56]. This may be due to their stronger swimming ability, greater attraction to light, or due to selective predation of smaller individuals within the trap [29, 56, 57]. However, Chicharo et al. [23] found three types of light trap to have similar and less variable catch than plankton nets for fish larvae. Vilizzi et al. [57] found light-traps protected by a mesh had many more juveniles and larvae than the traps without a mesh. The gut content of fish in the mesh-less traps showed that one species in particular had been preying on larvae and juveniles. Similarly in freshwater, Ulrich [58] observed that insects were being eaten by fish as they approached a light-trap and that a cage around the trap was necessary to enhance the light trap's effectiveness.

Table 4 Types of illumination used in light traps

Light type	Advantages	Disadvantages	References
LED	Very energy efficient, robust, many colours	Light is directional not 360 degrees	Gyekis et al. [79]
Chemical (Cyalume or glow stick)	Low failure rate, inexpensive, robust, many colours, 360 degrees of light	Light intensity is low and variable; light intensity may be affected by temperature	Barr [45], Holmes and O'Connor [72], Kissick [73], Kehayias et al. [84], Costello et al. [41]
Incandescent	Widely available, 360 degrees of light	Uses a lot of power, emits heat as well as light, fragile	Faber [71], Floyd et al. [39]
Fluorescent	Bright, energy efficient	Only one colour, fragile	Aiken [74], Kawaguchi et al. [33], Doherty [24]
Halogen	Very bright	Requires a lot of power, must be tethered to large battery, produces heat, fragile	Hernandez Jr and Shaw [64], Lindquist and Shaw [86]

Table 5 Abiotic factors affecting light trap catch

Abiotic factor examined	Results	References
Current	Light traps were not as effective in catching larval fish in a high current area as opposed to a low current area Light traps that were allowed to float with current had higher catch rates	Anderson et al. [48] Thorrold [60]
Turbidity	Catch rate decreased with increasing turbidity for larval fish	Lindquist and Shaw [86]
Sampling duration, and time of day and night	No difference in time of night catches for larval fish There were two peaks in catch rates of invertebrates, one near dusk and one near dawn	Thorrold [60] Tranter et al. [93]
Lunar cycle	Highest catch rate at new moon and lowest catch rates at full moon Highest catch rates at the third quarter moon (i.e., day 22–24 of the lunar cycle) though not consistent for all species	Hernandez Jr and Shaw [64] Sponaugle and Cowen [47]
Depth of sample	Highest invertebrate catch rates were found closest to the benthos For larval fish, catch rate varied with different species having peak catch rates at different depths	Tranter et al. [93], Tor et al. [92] Fisher and Bellwood [77]
Tidal effects	No tidal effects Highest catch rates at low tide	Chícharo et al. [23] Beckley and Naidoo [70]

Abiotic considerations

Variability in light trap catch may be related to turbidity, current, sampling time, lunar cycle and time of year (Table 5). The turbidity affects the distance the light reaches and the composition of the water may affect what wavelengths are transmitted [59]. Increased current can lower catch rates [40, 42, 60]. Fast currents can make it impossible for less mobile species to reach or enter the trap, even if they are attracted by the light [48]. Currents may also affect the stability of a trap causing it to move or rotate which may impede entry into the trap. In our use of light traps for teaching, we found very few animals were captured in light traps deployed in tidal currents or moved by wave action.

Sampling times and duration are likely to affect catch composition. The diel vertical migration of plankton, and nocturnal emergence of benthic animals into the plankton [61–63] will affect the distribution of species

in light trap samples. The tide may affect catch either through its effects on animal behaviour or on current speed and direction. The phase of the moon has been shown to affect catch rates, generally increasing catch at times when the moon is less bright, though its impact may differ between species [47, 64]. Fincham [55] found that early night catches of amphipods were dominated by infaunal species while in the hours before dawn amphipods that inhabited the algae made up the majority. However, sampling the whole night can result in greater predation within the traps [65]. Thus, further research is needed into the relative benefits of sampling for short periods or overnight.

Recommendations

Given the success of light traps in collecting marine fish and invertebrates, they merit investigation for monitoring marine invertebrate biodiversity, in particular for

monitoring mobile benthic macrofauna which are difficult and time-consuming to sample by other means. This fauna is a key link between primary producers and high trophic level taxa, including commercially important fish. Monitoring the biodiversity of these macrofauna may prove even more important as their abundance may be affected in ways we do not yet realise. For example, due to the consumption of inedible plastics by plankton and/or fishing-induced trophic cascades [66]. In addition, the traps capture a variety of life-stages of both benthic and pelagic taxa whereas other methods are selective for these environments.

The option of low cost light trap construction is another advantage over other sampling methods. The materials can be as simple as a water bottle and a light source, materials that can likely be found the world over. A bottle trap we used cost less than \$5 to build. The samples can also be taken passively, which means multiple locations can be sampled simultaneously giving a more complete picture of biodiversity over a large area. Finally the condition of the organisms which are collected is excellent which aids morphological identification. Specimens can be easily separated for archiving in reference collections, and samples could also be analysed by eDNA methods [3].

Light traps are limited to areas of low current and their effectiveness may be curbed by turbidity. However, it must be recognised that every sampling method is biased [3, 67]. To implement the use of light traps for monitoring benthic biodiversity the design, biases and abiotic factors need further research. Given the potential efficiency of the quatrefoil trap it may prove to capture most animals. However, such abundance may come at a higher cost of construction. The type of light used in this trap could vary, but for robustness and cost either an LED light or a chemical light would be the best choice. Small traps of 1–2 L volume appear adequate. Sampling all night may avoid missing out on nocturnal variation in species' abundance, but sampling for 1–2 h after dusk may be more time efficient and reduce within trap predation. A shorter sampling time period would also help staff monitor traps where disturbance by changing weather conditions or curious members of the public may be a concern. As current and turbidity are known to affect catch rates, recording these measurements would be useful in interpreting any catch results. Simple low-cost methods for monitoring these conditions also merit development. Further investigation into between-sample variation is also needed to understand how well the catch of light traps reflect the biodiversity in a given location, and how many replicates are required for each sampling occasion.

Biodiversity monitoring needs methods that can be standardised internationally, are low cost, easy to use, and produce verifiable data on species composition and relative abundance. With further research to understand how factors may influence light trap catches at local scales, they are a promising method for mobile benthic macrofauna and zooplankton. They would thus complement emerging non-destructive methods for sampling fish and other vertebrates (e.g., using video and direct observations), and emerging methods for using artificial substrata to census sedentary and sessile biota [3, 68, 69].

Additional file

Additional file 1. Tables listing the invertebrate and fish taxa captured in light traps, and associated references.

Authors' contributions

LEM conducted the literature review, compiled the data, and led writing of the paper. MJC initiated the study, advised on the data analysis, and co-wrote the paper. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its Additional file 1.

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