Towards an optimal design for ecosystem-level ocean observatories

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Abstract

Four operational factors, together with high development cost, currently limit the use of ocean observatories in ecological and fisheries applications: 1) limited spatial coverage; 2) limited integration of multiple types of technologies; 3) limitations in the experimental design for *in situ* studies; and 4) potential unpredicted bias in monitoring outcomes due to the infrastructure's presence and functioning footprint. To address these limitations, we propose a novel concept of a standardized "ecosystem observatory module" structure composed of a central node and three tethered satellite pods together with permanent mobile platforms. The module would be designed with a rigid spatial configuration to optimize overlap among multiple observation technologies each providing 360° coverage around the module, including permanent stereo-video cameras, acoustic imaging sonar cameras, horizontal multi-beam echosounders and a passive acoustic array. The incorporation of multiple integrated observation technologies would enable unprecedented quantification of macrofaunal composition, abundance and density surrounding the module, as well as the ability to track the movements of individual fishes and macroinvertebrates. Such a standardized modular design would allow for the hierarchical spatial connection of observatory modules into local module clusters and larger geographic module networks, providing synoptic data within and across linked ecosystems suitable for fisheries and ecosystem level monitoring on multiple scales.

Key Words:

Ocean observatories, Ocean technology, Ecological monitoring, Networks, Coenoclines, Deep-sea, Behavior, Optoacoustic technologies, Passive acoustic, Fish sound, Cyber interfaces

Introduction

Four operational factors, besides development costs, limit applicability of existing ocean observations systems for use as tools in fisheries and ecosystem level applications: 1) limited spatial coverage; 2) limited integration of multiple types of technologies (i.e., multiple modalities of observation); 3) limitations in the experimental design for *in situ* studies; and 4) potential unpredicted bias in monitoring outcomes due to the infrastructure's presence and functioning footprint. These limitations have slowed the spread of ocean observatory use toward fisheries and other ecological applications (e.g., benthopelagic coupling or connectivity), highlighting the need for efforts to improve observatory design (e.g., Handegard et al. 2013, Locascio et al. 2018).

Our objective is to propose how ocean observatories, combined with other observational sampling technologies, can be better designed from fisheries and ecology perspectives for the monitoring of marine ecosystems and their connectivity through coenoclines (i.e., a gradient of communities) formed along depth, latitude, and geographic gradients. What is unique about our suggested approach is that systems are designed from the beginning for ecosystem-level observations on large spatial and temporal scales, and to be replicated in many locations for global implementation. In order to meet these objectives, observatories need to be highly standardized and produce quantitative observations that are comparable among locations and over time. We present a 'straw-man' concept (i.e., one intended to stimulate discussion and refinement within the scientific community) of an "ecosystem observatory module" system that is based on a standardized modular platform design (hereafter referred to as the "module") consisting of a central node and three tethered satellite pods (hereafter referred to as "satellites"). By modular, we mean to suggest that the platforms should be designed so that they can be prefabricated, and therefore produced at lower cost, but be flexible enough to allow customization and implementation in different habitats. Such a design serves two purposes: first it provides directly comparable data among different locations, and second, it will encourage wider implementation of observatories around the globe. Most of the instrumentation we propose to assemble on each module has already been developed and implemented in some existing cabled observatories, though significant improvements in capabilities and reduction in cost are needed (see review in Aguzzi et al. 2019). In addition, much of the software needed to realize large scale observatory networks that are useful to fisheries scientists, resource managers and ecologists are still in the early stages of development (Juanes 2018, Allken et al. 2018, Marini et al. 2018a,b). Therefore, the development of data delivery systems that are accessible to a wide range of stake-holders from different disciplines and backgrounds is of vital importance for the effective use of ocean observatories for fisheries and ecological application (Perlman et al. 2019). Hence, we place an emphasis on the importance of designing data packaging and delivery systems in concert with the observatory structural and instrumentation design, rather than as an afterthought.

The implementation of permanent monitoring systems should deliver data on animal movement across habitat gradients (Aguzzi et al. 2015) and energy flux interchange (Thomsen et al. 2017), providing measures of biodiversity and ecosystem functioning (Aguzzi et al. 2019). Spatiotemporal variations in population abundances and associated demographic indices could then be used to track the status of ecosystem services such as fisheries resources. Major components necessary for our concept of an ecosystem-level ocean observatory networks include: 1) spatial quantification of organism abundance, density and biomass, through cross-referencing of data obtained from multiple observation technologies, 2) quantification of the impact of the observatory structure and operation of its instruments on the local biota, 3) a design for use of observatories as *in situ* laboratories, 4) deployment of spatial clustering to optimize observation on multiple spatial scales over appropriate coenoclines, 5) integration of ocean observatory data with observational data collected through other sampling methodologies (e.g., ship, satellite, drifter and buoy-based surveys, and animal-borne devices), 6) implementation of automatic data processing, such as detection of fish images, or sounds, to enhance data analysis by end-users, and 7) seamless presentation of multiple data streams to end-users that are synchronized in time across all instruments within a module and ultimately across all module locations.

We have organized our discussion starting with a brief summary of ocean habitat connectivity to provide context, followed by a description of our proposed ecosystem observatory module and its components and a description of how modules can be combined into clusters and networks to monitor along habitat gradients and coenoclines. A description of surveillance, modelling and forecasting of observatory data is followed by a description of how observatories can be integrated with animal-borne technologies, and a description of cyber developments needed to support monitoring networks and to provide access to users of different backgrounds. The final section before the concluding remarks is an appeal for the incorporation of observatory systems into commercial development projects such as windfarms, to serve as partial mitigation for ecosystem impacts by providing humanity with extensive ecosystem monitoring capability within the ocean realm.

Background: ecosystem connectivity

Current ocean observatories have limited applicability towards fisheries and ecosystem monitoring, in part because oceanic habitats exhibit complex linkages that operate on many different scales. Here, we present a brief summary of ocean ecosystem connectivity to provide context for our rationale of proposing highly standardized observatories that are organized in hierarchical spatial configurations to enhance quantification of ecosystem attributes along habitat gradients or coenoclines.

Researchers have long known that marine ecosystems are intricately linked through passive and active mechanisms for matter and energy transference. For example, estuaries serve as an important direct and indirect source of nutrients for coastal marine waters and thereby help to sustain coastal and deep-water fisheries (e.g., Teal 1962, Haines 1979, Nixon 1980, Odum 1980, Pomeroy & Wiegert 1981, Dame et al. 1986). Passive processes involve bi-directional fluxes of nutrients, pollutants, and plankton carried by water movements such as runoff, river flow, tides, up and down-welling, storm events, and dense shelf-water cascading, all acting along a habitat gradient from freshwater to coastal areas and to the deep sea (**Fig. 1**; Canals et al. 2006, Afonso et al. 2014, Puig et al. 2014, Rogers 2015, Thomsen et al. 2017). Relevant active processes also contribute to energy/matter transference in the form of rhythmic and arrhythmic population movements across seabed and water column depth gradients, such as Diel Vertical Migrations (DVM), which represent the largest natural daily movement of biomass on the planet (e.g., Graeme et al. 2010, Doya et al. 2014, Aguzzi et al. 2015b, De Leo et al. 2018; **Figs. 1 and 2**).

Mechanisms that regulate nekton distribution and movements along bathymetric and latitudinal coenoclines are similar and involve interactions between environmental (e.g., temperature gradients and cyclic fluctuations) and biological conditions (e.g., food and shelter availability and predation risk) (see reviews in Rountree 1992, Deegan et al. 2000, Rountree & Able 2007, Aguzzi & Company 2010, Aguzzi et al. 2011a). Horizontal linkages have been referred to as the 'chain-of-migration' (Rountree 1992, Deegan et al. 2000, Rountree & Able 2007), while vertical migrations have been referred to as the 'ladder-of-migration' (Vinogradov 1953, 1955, 1971). Mechanisms for linkages along a depth coenocline from the photic to disphotic pelagic zones, and aphotic to the dark benthic deep sea include: 'organics rain' (Vinogradov 1971, McCave 1975, Honjo 1980, Alldredge & Silver 1988, Thomsen et al. 2017), ontogenetic (i.e., with size or life-stage) vertical migration of organisms (e.g., Merrett 1978, Wakefield & Smith 1990, Kobari et al. 2008, De Leo et al. 2018), and cyclic vertical migrations such as observed in the Deep Scattering Layers (DSLs, Vinogradov 1953, Marshall 1971, Longhurst 1976, Mauchline 1980, Naylor 2010, Aguzzi & Company 2010, Aguzzi et al. 2017). In particular, rhythmic movements also occur in endobenthic burrowing or burying behaviours, within the benthic boundary layer across shelves and slopes (nektobenthic migrations), and through different water column depth strata movements (DVMs) (Aguzzi & Company 2010). Indirect day-night synchronization of biological activity in deep-sea aphotic realms may also occur due to the movements of deep-scattering layer organisms (e.g., Irigoien et al. 2014). These rhythmic movements may also be accompanied by changes in background illumination at the seabed, when species constituting the scattering layers are bioluminescent (i.e., bioluminescence panoramas; Aguzzi et al. 2017).

All these types of ontogenetic and rhythmic (e.g., diel and seasonal) movements produce energy fluxes that affect the functioning of ecosystems connected through a coenocline (Rountree & Able 2007, Aguzzi et al. 2011a; **Figs. 1 and 2**) which are difficult to quantify with isolated ocean observatories. Accordingly, any technological development dedicated to ecosystem exploration, monitoring, and ultimately management (*sensu* Danovaro et al. 2017) should be planned by combining Lagrangian sampling strategies (i.e., capable of tracking individuals and population movements) as well as Eulerian approaches (i.e., a ‘snapshot’ capable of characterizing locally the community changes produced by species displacements). For the former strategy, large scale movements of animals are being studied through telemetry *via* satellite (Hussey et al. 2015). Notwithstanding, only a few environmental parameters (e.g., depth and salinity) and no other ecological features (e.g., species interactions) are measured as explanatory factors of behaviour. For the latter strategy, a virtually holistic environmental monitoring approach is possible, but typically at a fine scale which can be difficult to scale-up to larger systems. Accordingly, a merger of both strategies would be possible by the establishment of networks of monitoring stations that allow animal and population tracking at a high rate, in a simultaneous fashion across large geographic scales and across latitudinal and depth gradients.

In this context, fisheries scientists have recognized the need to move from single species to ecosystem-based management approaches, but progress has been slow due to the complexity of coenoclines and the difficulty of obtaining synoptic data on appropriate scales (e.g., Marshall et al. 2018). Fishery management agencies can simultaneously advocate for no-take zones (i.e., static management approach) as well as for measures dedicated to the tracking and quantification of moving stocks (spatially dynamic approach) (Maxwell et al. 2015). This point is crucial as many Essential Fish Habitats (EFH, e.g., spawning or nursery areas) are not permanent in time, thus the establishment of Fishery Restricted Areas (FAO 2018) or other spatial management measures for fish and habitat protection could follow an adaptive approach (Walters 2007). Such a spatially dynamic approach will require different pathways for technological development in species and ecosystem monitoring. Such an approach is currently being pursued in the development of a cross-communication capability of cabled observatories with animal-borne technologies (e.g., hydrophones for acoustic tag recognition; Hussey et al. 2015).

Marine strategic areas are defined as ecologically iconic zones where multiannual surveying, as carried out by vessel-oriented technologies, is strongly recommended for scientific or management purposes (Aguzzi et al. 2019). Biological data on species demographic indicators (e.g., density, size and biomass), community composition (i.e., richness) and the effects of environmental controls on biodiversity obtained in this way for one iconic zone could be scaled to other areas with similar geomorphologic and oceanographic features as similar seascapes (Danovaro et al. 2017). Relevant areas have been and continue to be instrumented with different types of pelagic and benthic multiparametric platforms deployed as part of observational networks (Tunnicliffe et al. 2003, Barnes et al. 2013), providing different levels of monitoring capability and manipulative interventions (e.g., ONC 2019, OOI 2019). However, we propose that such large networks can be improved by the development of more standardized platforms constructed in a modular design, and with an increased focus on obtaining temporally and spatially overlapping data from multiple observation technologies.

Our design also seeks to address concerns about the footprint of observatories on the local biota and habitat characteristics for two reasons: 1) measurement bias, and 2) degree of impact by the structures' presence and functioning on the local environment (typical sizes of the main components of observatory systems are around 3-5 m on each side and 2-4 m in height). Since any observatory will function as an artificial reef and thereby modify the local habitat characteristics that we are attempting to measure, more attention is needed to understand the attraction, repulsion and residency effects of the structure and its operations (e.g., pan-tilt camera motor noise, mobile platform noise and illumination at imaging) on sessile and motile species, and their interactions on each other (e.g., the establishment of fouling communities on the structure could influence the local trophic structure). Over time, such developments can result in enough changes that the observatory data will no longer reflect the habitat that it was designed to observe. Observatories are also invasive technologies that produce noise, lighting, and motions that can be foreign to the habitat under study. It is important, therefore, that systems be designed to better understand the invasive impact of observatories to comply with international legislation (e.g., underwater noise as ecological descriptor; Audoly et al. 2016, 2017).

The Ecosystem Observatory Module

A conceptual schematic of our proposed ecosystem observatory module and its components is provided in **Figure 3** and the function of each sensor and component device are outlined in **Table 1**. Standard components of each module would include: 1) central node and associated instruments, 2) mobile platforms, 3) three satellite pods, 4) a passive acoustic array, 5) a spatial configuration and software to optimize cross-referencing among observational data, and 6) autonomous instruments. Optionally, some modules would be enhanced with the addition of a pelagic satellite to collect data on sea-surface and water-column organisms and conditions. Unlike existing observatories, our design emphasizes the importance of using nearly identical modules at different locations around the globe that acquire time-synchronized data integrated across multiple spatially overlapping observation technologies (**Fig. 4**).

The central node and its instruments

The central node serves as the primary instrumentation platform, power supply, and data link for the module. It also houses dockage, data transfer links, and power supply for three types of mobile platforms (**Fig. 3, Table 1**). Standard observation instruments on the central node would include stereo-video cameras, acoustic imaging sonar cameras (e.g., Dual-frequency identification sonar: DIDSON), and bioacoustic echosounders, as well as a passive acoustic system capable of recording sounds over a biologically relevant bandwidth (1Hz to 150 kHz). In order for these systems to provide observations useful for ecosystem-level monitoring, they must provide spatially and temporally quantifiable data. For example, pan-tilt high-definition cameras that are often standard on observatories are not conducive to the collection of occurrence data on even a presences/absence level because the direction, depth, and angle of the field of view are constantly changing and, hence the absence of organisms cannot be determined.

To achieve the desired quantification, our module design requires that each technology provides 3-dimensional data over 360° around the module, and overlap with each other to the maximum degree possible (**Fig. 4**). However, each device will have different ranges, beam-angles, and time-resolutions which must be integrated to provide seamless views to the end-user (see Cyber developments section below). Comparison of data from the overlapping 3-dimensional views provides the ability to cross-reference data to improve identification and measurement accuracy (**Fig. 4**). We recommend that stereo-video cameras be used to obtain the 360° view around the central node because they also provide 3-dimensional location and organism size data as proposed in Bosch et al. (2019). Although we are not aware of previous stereo-video camera applications on existing observatories, they have been widely used in fisheries and ecological applications, including deep-sea applications (e.g., Harvey & Shortis 1998, Shortis et al. 2008, Williams et al. 2010, Bonin et al. 2011, Merritt et al. 2011, Shortis et al. 2016, Williams et al. 2018). It is important that these devices not be under user control, because they must provide the maximum stability of views over time (i.e., constant field of view within the device's limits). However, we also recommend that each module's central node additionally contain at least one pan-tilt video camera under user-control, to allow the examination of specific phenomena (e.g., burrow emergence of different individuals or rate of access to carrion), and to help validate the identification of organisms observed with the fixed video or other observation instrument.

Mobile platforms

Three types of mobile platforms would be docked at the central node of each module, including a seafloor Crawler, neutrally-buoyant Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). Although there is some redundancy among ROV, AUV and Crawler platforms, each provides unique capabilities and have different negative properties. All three types of platforms are useful for surveying habitat and organism distribution surrounding the module, and each can be used to investigate specific phenomena observed around the module, and can aid in the identification of unknown targets detected by the video, acoustic imaging sonar, echosounder and passive acoustic array.

ROVs and AUVs are both navigating assets, the AUV has a much greater range and is not limited by its tether. In contrast, although hampered in some ways by a tether, the ROV has manipulative capabilities (i.e., by robotic arms), can carry larger payloads and can be directly controlled by a user in real-time. The AUV provides the best mechanism for mapping and monitoring habitat and biota (benthic and pelagic) of the area surrounding a module and the larger area encompassed by the module’s satellites. In addition to providing habitat mapping capabilities of the area immediately surrounding the central node, the ROV can also be used to place autonomous instruments, exchange satellite payload packages, and service all infrastructure components of the module (Sivčev et al. 2018). The ROV can also be equipped with push-corers in order to sample sediments or rocky formations. The ROV’s high mobility also allows important functions such as the monitoring of the fouling community, interactions of organisms with the infrastructure and its instruments, and faunal residence (e.g., sheltering).

A drawback of both AUVs and ROVs is that thrusters must be on even when hovering at a station, thus creating high levels of noise and turbulence that limit their ability to conduct unbiased sampling and observations at a specific location for any period of time (Rountree & Juanes 2010, Durden et al. 2016a). An important, but often overlooked, noise problem with ROVs is that their acoustic tracking and guidance systems produce intense broadband noise that may influence animal behaviour, and can also bias measurements of the acoustic properties of biological sounds (Rountree & Juanes 2010). In addition, the intense tracking pings make it harder for a human user to process soundscape data (Rountree *pers. observ.*). Another drawback of ROVs is the need for lights for operations (Rountree & Juanes 2010). The main limitations of AUVs are related to the development of suitable docking infrastructures that can provide for data downloading, and fast inductive recharging of batteries to increase AUV operating time.

The Crawler can more effectively conduct point-census surveys that can provide data at specific locations for extended time periods (minutes to hours), during which noise production and turbulence can be substantially reduced compared with the other mobile platforms. A drawback to the Crawler is its physical disturbance of the benthic habitat and impact on benthic organisms along its movement track, but this can be reduced to a narrow seabed parcel, by limiting the Crawler to a constant corridor for displacement (Chatzievangelou et al. in review). Since such potential impacts would be magnified in the area around a permanent observatory, we recommend that Crawlers be operated on pre-determined and constant tracks to minimize habitat disturbance (**Fig. 3**).

Tethered satellite pods

The three standardized satellites of each module would have several functions: 1) provide observational redundancy and spatial overlap of observations with the central node observations to assist in organism detection, identification, and development of 3-dimensional distribution maps in the area surrounding the module (**Fig. 4**), 2) provide observation of biotic responses to the central node and its mobile platform presence and operations, and 3) to serve as platforms for changeable instrument packages designed to address specific research hypotheses.

A central premise of our proposed ecosystem observatory module design is that it includes multiple modalities of observation that are synchronized in time and provide the maximum spatial overlap. Therefore, the spatial configuration is dependent on optimizing the overlap among the systems under local conditions, as well as limitations of tethering and ROV and Crawler access to the satellites. We suggest that in many locations satellites placed at 120° intervals and at distances on the order of 10 m from the central node would be most suitable (**Fig. 4**). Minimally, each satellite would come with standard stereo-video cameras capable of capturing a 360° view around the satellite. Ideally, they would also include the same acoustic imaging sonar and bioacoustic echosounders instruments as those on the central node, but at the present time these systems are prohibitively costly to achieve the ideal redundancy and overlap within the module area. As these technologies advance sufficiently to allow cost-effective 360° coverage, they should be added to the satellites to improve spatial overlap over a larger area surrounding the central node.

Observational data obtained by the satellites of the area surrounding the central node and by the central node of the area surrounding each satellite, would provide a powerful means of determining faunal interactions with the structures, including behavioural reactions to instrument operations (e.g., lights and sounds, **Fig. 4**).

Ocean observatories should be thought of as permanently instrumented areas where scientists of different backgrounds have an opportunity to perform manipulative experiments, favouring iconic environments such as the deep-sea for example, and resulting in a transition from a still largely descriptive science toward a more experimentally-based (i.e., hypothesis-driven) approach. In order to better serve as platforms for hypothesis-driven research objectives, the satellites need to be designed with an infrastructure that allows for 'slide-in slide-out' exchange of experimental payloads for hook-up to power and data transfer. Examples of potential payloads might include settlement trays, experiments on the response of biota to artificial light regimes (useful for behaviour studies but also to examine the impact of observatory lights), observation of biota response to a bioluminescent light, response to various baits, response to sound playback experiments (useful to understand behaviour and also the impact of observatory generated noise on the biota), experimental attempts to mark or tag biota through ingestion of tags or automatic capture, tag and release mechanisms (having the dual purpose of studying fish movements and residency, and using the observatory structure as habitat), the effects of new colonized substrates on species and succession experiments, habitat manipulation experiments such as predator exclusions, microcosm and mesocosm experiments, and many other possibilities.

Passive acoustic array

Passive acoustic monitoring of fishes and invertebrates has become an important tool in fisheries and ecosystem studies (Rountree et al. 2006, Luczkovich et al. 2008), however, inherent problems have slowed its more widespread application, including lack of catalogues of fish sound data (Rountree et al. 2002), lack of information on source levels and detection ranges, and lack of sufficiently developed autodetection software (Rountree et al. 2006, Luczkovich et al. 2008). The use of multiple observation technologies to aid in the *in situ* validation of sound source identity, source level, and detection ranges is in its infancy (Rountree et al. 2003, Rountree 2008, Rountree & Juanes 2010), but a combination of using a passive acoustic array with video for the *in situ* identification of unknown fish sounds has recently been demonstrated (Mouy et al. 2018). The application of passive acoustic arrays for localization and cross-reference with other forms of observation on ocean observatories are particularly promising, especially in the deep-sea where many fishes possess sonic muscles that are presumably used for sound production (Rountree et al. 2012, Wall et al. 2013). Calls for the increased use of passive acoustics for fishes and invertebrates to be incorporated into ocean observing systems have been made at workshops for decades (Rountree et al. 2003, Acts 2007, Rountree *pers. observ.*), but have been slow to be implemented (Locascio et al. 2018). It should be emphasized that incidental sounds produced by fishes and invertebrates as by-products of movement, feeding or physiological processes, can be important markers of species identity, and useful for monitoring temporal and spatial patterns in the associated behaviour (Rountree et al. 2006, Rountree et al. 2018). Thus, passive acoustics can be a useful tool for monitoring both vocal and non-vocal organisms and their behaviours at observatories.

Because of the high promise of passive acoustic monitoring as an important tool in ocean observatories, we include a hydrophone array in our module design. At the minimum hydrophones should be placed on the central node and each satellite to create a four element 3-dimensional array that can localize on sounds originating near the central node. However, a greatly improved ability to localize on the low amplitude sounds created by many fishes and invertebrates could be achieved by placing compact arrays of six hydrophones on each element (*sensu* Mouy et al. 2018), or by placing additional hydrophones at intervals along the tethers from the central node to each satellite (**Fig. 3**).

Stand-alone sensors and other devices

Autonomous instruments and recording devices (e.g., Corgnati et al. 2016, Marini et al. 2018a), deployed and serviced by the mobile platforms, would be incorporated into the area surrounding the module to provide unique data on biota in the surrounding habitat, and additional opportunities for *in situ* experimentation (**Fig. 3**). For example, autonomous video recorders could be placed close enough to individual fish nest sites, or individual sessile invertebrates, to use short-range infra-red lighting to make long-term observations on microhabitat use, behaviour, and species associations. Autonomous instruments could be also used to measure gradients in conditions moving away from the central node, or specific satellites in an effort to quantify the effects of habitat heterogeneity on animal presence and habitat use and the observatory's influence on environmental conditions, habitat structure, and organism distribution (i.e., distinguish between natural variation and variation resulting from effects of the module). Many other types of autonomous devices can be envisioned to carry out hypothesis-driven experiments such as small mesocosms, settlement trays, exclusion cages, benthic animal traps, etc.

Importance of observation data overlap

Time synchronization and spatial overlap of all observation data, within the resolution limits of each type of instrument, within a standardized spatial configuration is one of the most important attributes of our proposed ecosystem observatory module design as it allows for the cross-referencing needed for species detection, identification and tracking (**Fig. 4**). Consideration of how to best optimize the spatial coverage and overlap of observation data and how it can be packaged for users, should be part of design process for implementation of our ecosystem observatory module concept.

Stereo-video cameras, acoustic imaging sonar cameras, and horizontal multi-beam echosounders should each provide a 360° field of view around the central node. Although the technology to do that is currently available if multiple instruments of each type are deployed, advances in systems to reduce cost and simplify deployment on ocean observatories are needed. Stereo-video cameras on each of the satellites provide additional video coverage to the module. Ideal spacing between the central node and satellites is determined by optimizing overlap among spatial coverage of all instruments for local conditions. Stereo-video cameras provide the highest accuracy of species identification, size and location in the area surrounding the module, but are limited to periods of natural or artificial lighting. Acoustic imaging sonar provides accurate location of targets, but poorer size resolution and species identification. However, it is not limited by lighting. Horizontal multi-beam echosounders provide highly accurate 3-dimensional location over a large spatial area surrounding the module, but identification is limited by the accuracy of back-scatter target strength data which are influenced by fish size and orientation to the acoustic beam, creating uncertainty in multi-species scenarios. Sounds detected by the passive acoustic array can be used to identify species when sounds are well known, but until detailed catalogs of fish and invertebrate sounds become available, most sounds detected and localized will be from unknown sources.

Cross referencing of echosounder data with acoustic imaging sonar, video and passive acoustic data, can provide valuable validation of target strength data for organisms and thereby enhance biomass estimations around the observatory, as well as provide target strength data for other independent conventional bioacoustics surveys (e.g., traditional fisheries pelagic surveys that rely on accurate target strength data for bioacoustic assessment of fish stocks). Similarly, cross referencing of acoustic imaging sonar with echosounder, video and passive acoustic data can provide identification validation of acoustic image targets in the near-field and echosounder targets in the far-field. Finally, cross-references of unknown sounds localized by the passive acoustic array with video, acoustic imaging sonar, and echosounder data, can provide sound source identification and quantification of source level and detection range (Rountree 2008, Mouy et al. 2018).

Simultaneous observations from all technologies would make it possible to track organisms continuously as they move around the module (**Fig. 4**). Therefore, at each location, data on changes in fish orientation and location can be used to quantify their influence on echosounder target strength. As more and more data are compiled, accuracy of identification and tracking, and estimates of fish size, abundance, density, sound source level, and sound detection range, improve. A 360° view around the observatory by multiple observation technologies allows users to estimate the abundance of biota per area, while correcting for movements of individual fish and other organisms. A fish swimming in circles around the structure can be counted accurately as one individual, rather than multiple individuals moving in and out of a video field of view. To obtain this type of data, modules must be configured with satellites in close enough proximity to provide adequate coverage of mobile biota (**Fig. 4**).

Optional pelagic satellite

The ecological monitoring of modules can be significantly enhanced by the addition of surface and water-column assets that can combine benthic observations with water-column and surface observations to monitor both surface associated organisms and conditions as well as those of the water column (**Fig. 5**). Besides providing a monitoring capability of the pelagic ecosystems, ecosystem observatory modules enhanced with a pelagic satellite can provide unprecedented information on pelagic-benthic ecosystem connectivity. This can be accomplished by placing a buoyed surface platform in contact with a module *via* an instrumented mooring line. Surface buoys and mooring lines have the potential capacity for numerous instruments to be distributed along the water column to synoptically monitor fine-scale hydrographic and biogeochemical parameters as for example corrosive (i.e., low pH, high pCO2) oxygen minimum zone waters seasonally intruding onto continental shelf-edge zones (Juniper et al., 2016). Instruments can be either fixed (e.g., Bahamon et al. 2011) or movable as yo-yo systems for fish monitoring from decommissioned platforms (Fujii & Jamieson 2016). They can also serve as access platforms to allow some types of maintenance of bottom mounted observatories (depending on depth and conditions).

Each buoy would be fitted with a weather station, microphone and video camera to monitor surface conditions and shipping activity (e.g., OBSEA 2019, Aguzzi et al. 2011b). Recordings of aerial noises associated with weather, sea state, and shipping can be validated by the video and compared with simultaneous acoustic recordings from hydrophones, to provide important insight into the source of underwater sounds and help to quantify noise impacts on the aquatic soundscape. The surface buoy would also support downward projecting video, acoustic imaging sonar and echosounder instruments to provide similar capabilities to those of the bottom mounted instruments, and hence, valuable data on pelagic components of the ecosystem. All instruments would be plugged into the cabled observatory for data transmission and power source, with no need for satellite communication.

The development of a new cargo elevator technology (**Fig. 5**) would allow the rapid delivery and retrieval of instruments and materials to and from the module. For example, in combination with the module's ROV or Crawler, scientists could deliver a new experimental payload to one of the satellites, and remove the old unit. Another example would be to deliver fresh bait to a baited camera system, or to retrieve organisms captured by instruments at the module. An elevator system could dramatically increase our ability to deploy and retrieve materials to the module because it would no longer depend solely on the use of expensive ship-based submersibles or ROV bottom time.

Pelagic satellites can also be used as docking and communication stations for specially adapted aerial drones (**Fig. 5**). One of the most important applications of drones would be to map spatial and temporal distributions of marine birds, mammals, turtles and large pelagic fishes (e.g., Toonen & Bush 2018). Pleustonic and neustonic components of the ecosystem could also be mapped including distributions of jellyfish, *Sargassum* and other flotsam and the development of windrows. In addition, they can map the distribution of organic matter subsidies including kelp, and marine mammal carcasses, and also track pollution such as floating plastics, oil slicks and other pollutants. This can also be crucial to monitor alien species and forecast potential areas of invasion, as plastic debris and other floating materials contribute to the transfer of non-native species (Vetger et al. 2014). Drone systems are already being successfully developed to conduct passive acoustic surveys (Loyd et al. 2017). A communication tower on the buoy would enable researchers to communicate with the drones through a relay from the cabled observatory and also provide short-range communication with research ships and aircraft.

Satellite remote sensing has become an important tool in oceanography and fisheries monitoring (e.g., Santos 2000, Blondeau-Patissier et al. 2014) but ground-truthing of data is critical for accurate interpretation and modelling (Congalton 1991). The Southeast Atlantic Coastal Ocean Observing System (SEACOOS) included a pilot study of the potential for integration of satellite remote sensing and ocean observation systems (Nelson & Weisberg 2008), which found that coordination among data providers, management, modellers and users was a critical bottle-neck. Field validation efforts are important but expensive and difficult to coordinate. Observatory based drone sampling can also be used to enhance satellite remote sensing programs by conducting some types of field validation sampling if they are integrated to work together. Ecosystem observatory-based drones could provide a more cost-effective tool for obtaining oceanographic data for a wide range of measurements from sea surface temperature to primary production in order to tune satellite data interpretation and modelling. Some drones could be equipped with a payload of specialized equipment for specific projects, such as a chlorophyll fluorometer or for deployment of sonobuoys, drifters and expandable vertical profilers. Thus, integration of ocean observatories with remote sensing satellite systems can improve the accuracy of spatial mapping of large-scale environmental conditions.

Ecosystem observatory module clusters and networks

In order to be able to provide meaningful ecological data at different spatial scales (i.e., from local conditions to geographic areas) accounting for key factors such as habitat heterogeneity along a coenocline (e.g., Rex & Etter 2010, Lecours et al. 2015, Zeppilli et al. 2016), local modules should be associated into a spatial hierarchy of clusters and networks, called ecosystem observatory module clusters and ecosystem observatory module networks. Adopting a highly reproducible module design for observatories should reduce costs and allow for replication of data at different locations.

The spatial configuration of modules within clusters and clusters and clusters within networks is critical to providing spatial and temporal overlap among the various observation technologies required for cross-referencing and validation. Experiments are needed to access the optimal configuration under local conditions. In these experiments a minimum of three modules within clusters and three clusters within networks are needed to insure at least minimal coverage and overlap. We suggest that adopting a cluster design of three modules separated on the order of hundreds of meters would be an effective way to scale-up data collection from individual sites to habitat (**Fig. 6**). At distances of hundreds of meters, bioacoustics coverage among the modules in a cluster would overlap to provide the ability to estimate water-column biota density in a homogenous fashion over a large area (0.5-1 km^2 or more **Fig. 6**), and to quantify the effect of module structure and operations on biota occurrence and behaviour. Cross-reference data from each module would greatly improve the accuracy of the identification and density estimation of biota within the cluster area, but well outside of individual modules, and allow for detailed benthic habitat mapping over the larger area encompassed by the cluster. Such coverage would facilitate accurate faunal abundance and density estimates necessary for fisheries and other applications, and reduce observatory bias on measurements due to attraction and avoidance responses of organisms to the observatory structures.

Finally, advanced AUV capabilities would enable the AUV to be used to map habitat and benthic biota distributions between and among modules within the cluster. In some scenarios, all modules within a cluster might share one AUV that patrols among them and can dock at any module. In other scenarios, AUVs provided by each module would provide the cluster with multiple AUVs for more rapid and detailed mapping. Observational data obtained from the AUV tracks can further increase our ability to validate the identity of bioacoustics and passive acoustic targets outside of the modules but within the cluster area. In some cases, AUVs might be programmed to investigate passive acoustic or echosounder targets beyond the range of the other observational instruments within a cluster area to improve identification and density estimates. Where feasible, an observatory cluster would include one enhanced with a pelagic satellite that can provide drone support for the entire cluster to enhance studies of vertical connectivity from the surface to the benthos at the cluster location.

Sentinel System

The hierarchical structure of the observatory systems we propose together with multiple synchronized observation technologies is critical to enable quantified monitoring on multiple spatial scales and elevates observatories from highly localized systems to broad-scale monitoring systems. Overlapping coverage and temporal synchronization of passive acoustic, stereo-video, acoustic-imaging, and echosounder technologies together with ROV and Crawler surveys, provide unprecedented quantification of organisms in the area immediately surrounding the module (**Fig 3, 4 and 6**). The echosounder, with data calibrated from cross-referencing observations from other technologies at the module, together with ROV and Crawler surveys, extends the region of high quantification of organisms to a considerably greater area around the module (**Fig. 4**). Thus, a cluster composed of three modules contains three areas of very high quantification which, in and of themselves, provides a high level of quantification of organism distribution within the cluster region (**Fig. 6**), but in addition high quantification of the greater area between the modules is achieved by overlapping echosounder coverage (which, again, provide data validated through multiple technologies at each module). Organism and habitat mapping throughout the cluster area via the AUVs (and in some cases aerial drones) provides another layer of quantification and additional cross-reference data for echosounder validation. Together, data from each of the modules, the AUV mapping and the overlapping echosounder provide an unprecedented quantification of organisms and habitat associations over a large area (on the scale of a 0.5-1 km^2) encompassed by an observatory module cluster. This can only be achieved through a careful consideration of the spatial configuration of modules within a cluster and use of overlapping spatial coverage of multiple synchronized technologies.

Observatory systems based on such a hierarchical clustered structure can then be deployed along a coenocline to form an observatory network we term a ‘Sentinel System’ (**Fig. 7**). A minimum of three observatory module clusters ‘’(i.e., nine modules arranged in a spatial hierarchy), would be needed to elevate the monitoring network from examination of local habitats to ecosystems and large geographic regions (**Fig. 7**). It should be clear, that such a sentinel system would ideally be one component of a larger monitoring effort that coordinates data from conventional ship, satellite, buoy-based and animal-borne, survey programs. For example, establishing a sentinel system composed of clusters (each of which provides high-resolution monitoring on a scale of 0.5 to 1 km^2) in the upper and lower sections of a major estuary (e.g., the Chesapeake Bay) and another on the continental shelf just offshore, would be effective at monitoring movements of coastal fishes that utilize the estuary as seasonal feeding or nursery grounds. Similarly, deployment along coastlines can provide information on the timing of seasonal movements of fishes and habitat connectivity along migration corridors. Sentinel systems would be useful to monitor migration patterns of fishes and invertebrates by documenting first detection, last detection, and residence period at different points along the gradient. Such a system would also be useful for monitoring the invasion of organisms into new territories (Juanes 2018), by placing clusters along the predicted invasion pathway.

Ecosystem surveillance, modelling and forecasting

Fixed and mobile platforms allow for an experimental approach to the study and monitoring of ecosystem functioning at different spatiotemporal scales (over kilometres and years). The combination of stereo-video, acoustic imaging, and echosounder imaging provides the ability to quantify abundance, size, and biomass of organism over a wide size range, as well as to identify multiple types of behavioural reactions to natural or artificial stimuli. In addition, the simultaneous acquisition of biochemical and oceanographic data can inform researchers of potential causative factors for observed behaviour and abundance patterns. However, automatic processing of the high-volumes of data generated by the observatories would be essential. Toward that end, we note that automated detection and classification methodologies based on the various observation technologies are rapidly advancing (e.g., Allken et al. 2018, Juanes 2018, Marini et al. 2018b). However, we suggest that our concept of an ecosystem observatory user data interface would greatly enhance the application, testing, and quality control of detection algorithms, by providing a simple platform for user aided system learning (see Cyber development section below, **Fig. 8**).

Ecosystem observatory networks can be used to estimate local species abundances derived from the image-based identification and counting of individuals, made possible through integration of multiple observation technologies (see **Figs. 4 and 8**). In addition, the methodology provides an ability to develop size-class frequency data and species biomass estimation based on the estimated size and counts of individuals (Durden et al. 2016b). Cross-referencing of data from ROV, Crawler, AUV and echosounder data with validation data from each module provides the ability to obtain standardized abundance and biomass data for the entire observatory network area (**Fig. 4, 6 and 7**). Simultaneous monitoring of a large suite of environmental factors such as temperature, turbidity, chlorophyll concentration and other biochemical factors, together with fine-scale temporal and spatial distribution patterns of organisms would provide important data on environmental regulators of species population structure and behavioural patterns. Temporal patterns in species richness, abundance, biomass, size-class structure and role of environmental regulators within an observatory network, supplemented with data from other monitoring programs, could provide the raw data needed to develop ecosystem modelling and forecasting programs for the habitat or region surrounding the network.

Data from multiple observatory networks could then be linked to make comparisons among areas, populations and environmental regulatory factors to develop regional and ultimately global monitoring programs. Spatially representative and long-term monitoring provides the ability to distinguish between population/community regulation by repetitive phenomena (e.g., rhythmic abundance variations due seasonal environmental changes, and ontogenetic migrations, spawning migrations, etc.; Aguzzi & Company 2010, Aguzzi et al. 2011a) from long-term (decadal and longer) processes such as shifts in species distributions due to climate change and changes in resource exploitation. If the information obtained from the observatory network system and associated modelling and forecasting programs is automated, it may be possible to develop ecosystem alarm protocols that detect anomalies in ecosystem parameters that might signal undesired environmental states such as impending population collapse of keystone species.

Integration of benthopelagic networks with animal-borne technologies

Cross-connection of ecosystem observatory module networks with free-moving Animal-Borne Sensors (ABS) technologies can also be envisaged. Inclusion of technology into the module design (**Fig. 3**) that allows communication with independent ABS is particularly promising for obtaining data on animal behaviour as well as data from animal-borne environmental monitoring programs (see for example the Animal Telemetry Network Implementation Plan 2016-2021, NOC 2016). Presently, data loggers connected to animals are getting evermore miniaturized (e.g., Nassar et al. 2018) and still primarily store oceanographic information about travelled seascapes (Fehlmann & King 2016, Wilmer et al. 2015), but only limited ecological information on intra- and interspecific interactions experienced by the traveller. This weakness is being corrected in part by the development of animal-borne cameras. Animal-borne video collection directly allows the derivation of ecological information, based on what is seen by individuals during their displacements (Moll et al. 2007). Moreover, the progressive miniaturization of implant components will eventually allow camera installation on animals of very different sizes (although filming may be constrained at night or in deep-water areas).

If both the observatory module and animal-borne technologies are capable of two-way communication, then data-intensive video-sampling by animal-borne technologies can be enhanced by dumping data to the observatory, thereby freeing up data storage and increasing their useful life-span. Similarly, modules can be tuned to receive telemetric data from tagged animals, freely moving across depths and basins (Hussey et al. 2015). This cross-communication can complement the monitoring capability of already existing pelagic and coastal-shallow networks (e.g., OTN 2019). Presently, for the development of technological tracking of epibenthic animals carrying an acoustic emitter, displacements can be measured into a network of moored receiving hydrophone stations (Rotllant et al. 2014, Tuck et al. 2015). Such development is necessarily limited by the range of hydrophone detection capabilities and could be potentially expanded, when animal tracking is assisted by moving platforms, delivering real-time data on their positioning. Tracking expansion is presently pursued by using wave-gliders and AUVs (e.g., Lin et al. 2016, Masmitja et al. 2017).

Cyber developments in support of monitoring networks

Networks of fixed and mobile units for coordinated ecological monitoring require not only hardware development but a concomitant suitable cyber architecture for data communication, processing, storage, and visualization of interrelated multidisciplinary data of different types (Florea & Buiu 2017). Moreover, cyber infrastructures should provide proper 'Virtual Research Environments' (VRE), which can be described as online collaborative environments that allow open access and program development for best science practices (Martin et al. 2019, Morrins et al. 2019, Pearlman et al. 2019). These VREs should be built on top of interrelated multiparametric data access platforms similar to those developed for the Ocean Networks Canada Web services API and Sandbox tool set (Rempel & Cabrera 2018). It is critical that such VREs serve as libraries of multiparametric data (e.g., imaging, acoustics, physical, biochemical) derived from the observatories, as well as open source automated classification and statistical analysis programs.

As ecology researchers increasingly deploy embedded sensor networks, they are being confronting with an array of challenges in capturing, organizing, and managing large amounts of data (Borgman et al. 2007). User navigation into network data banks and analysis capability requires the design of efficient interfaces between people and computers. Such a design should include all steps of information flow, from data collection at each sensor and platform to its global elaboration. This type of information flow framework is well described by Ecoinformatics (Michener & Jones 2012), which arose from the need to integrate environmental and information sciences to provide the language tools and standardization practices necessary to access and analyse massive amounts of heterogeneous data (e.g., by developing data banking).

Data integration would include several disciplines related to information technology that allow control of data collection, processing, integration, and use in VRE systems by multiple sensor technologies. The Sensor Web Enablement (SWE) approach defined by the Open Geospatial Consortium (OGC) standards (Del Río et al. 2018, Chaturvedi & Kolbe 2019) is a low-level specification of functionalities that allow any kind of compliant sensor to interact with other sensors, with human users or with properly defined intelligent services. Networks of Sensor Web Enablement (SWE) compliant sensors allow for a remote interaction by simply triggering them on and off, or by changing their acquisition configuration in order to adapt the monitoring activities for specific purposes. The intelligent services capable of interacting with the SWE compliant sensors are generally defined according to the Internet of Things (IoT) technology paradigm (Qin et al. 2016, Čolaković & Hadžialić 2018) which refers to the capability of making content and services understandable by devices without human involvement. To achieve this goal within the marine science and technology community, data science methodologies (Skiena 2017) based on artificial intelligence, should be capable of extracting the relevant content from the acquired data, then using this content for interacting with the SWE compliant observatory or for populating appropriate data repositories (e.g., the Copernicus or the SeaDataNet initiatives). For example, data acquired by SWE sensors, and managed by intelligent services could be of the biophony (sounds of known fishes, cetaceans, birds, unknown biological sounds, etc.), the geophony (natural sounds like wind, rain, thunder, waves, etc.), and the anthropophony (noise from ships, seismic surveys, and the observatory itself) which would then be utilized by sound type classification software to document spatial and temporal patterns in sound occurrence and correlations between biophony and anthrophony to assess noise impacts. SWE sensors could similarly be used for biogeochemical data or visual data acquired by stand-alone devices capable of communicating the relevant acquired information (Marini et al. 2018a).

Since all marine monitoring networks are increasingly service- and end-user oriented, their data management cyber infrastructures are also being upgraded to retrieve, store, and process data in real-time, acting as a cognitive system for data interpretation for humankind (Shenoi et al. 2015). Systems should enable any end-user worldwide to investigate ecological processes *via* interactive web interfaces, allowing navigation into banks of multiparametric big biological and environmental data (*sensu* **Fig. 8**). Responses should be visualized in the form of synthetic graphic outputs, highlighting significant global change trends and cause-effect relationships. Such visualization would be based on high-level data science activities performed within VRE capable of allowing non expert users to compose complex workflows based on tools with high technological and scientific content (Buck et al. 2019). Data output could be based on automated time series analysis (Aguzzi et al. 2012, Skiena 2017, Recknagel & Michener 2017) as well as on multivariate statistics, which would then allow modelling of biological responses to key environmental variables. The use of such powerful software tools on big biological and environmental data will transition ocean observatory systems from a largely descriptive to a more quantitative monitoring platform.

Data flow management from multiple observation technologies

It is critical that data streams from all the observation instruments and sensors be synchronized and maintained as relationally integrated data that are interoperable with other observation networks (see ONC's Oceans 2.0). Data should be enriched with the appropriate semantic information, that allow their retrieval by semantic-based search engines (Aguzzi et al. 2015a). A user annotating events in one data set should be able to seamlessly populate the same annotation in all other data streams (**Fig. 8**). For example, a user marking the location of a sound in the hydrophone recording, should be able to automatically locate the corresponding data position in video, acoustic image, echosounder and environmental data sets (e.g., ‘d’ in Fig. 8). Although observatories currently provide metadata containing information on observatory instrumentation functioning performance, maintenance status and functioning history, data quality assurance and control, calibration, etc. (Pirenne et al. 2018), this may not be sufficient for end-users who are not capable of cross-referencing all this information automatically, because it must first be downloaded and integrated by the users themselves.

A user interface that provides all module data integrated together in an interactive visual display would be a powerful tool for researchers (**Fig. 8**). For example, a user viewing a video would immediately see not only environmental and other observational data, but also the activity state of all instrumentation (e.g., lights on, rotary motor active, ADCP active, ROV thrusters on or off, etc.). Comparison of data from the overlapping 3-dimensional views in video, acoustic image, and echosounder windows provides the ability to cross-reference data to improve identification and measurement accuracy. For example, if a video detector identifies targets ‘a’ through ‘d’, its ‘ghost’ target can be displayed in the acoustic image and echosounder windows to look for matches, or to compare with automatic detections in those data sets. That will help a user determine if some detections are valid, or to identify unknown detection targets. The user could then download a data set containing all the attributes of the target based on the different observation types as well as corresponding environmental and operational state data. Such information can provide valuable clues to understand species response to the observatory and potential biases in behavioural observations, in addition to providing data on biota response to environmental conditions, and the raw data necessary to compile species abundance and volume density maps. The ability to seamlessly download data in these kinds of relational data sets is of utmost importance to encouraging widespread utilization of observatory data among scientists, resource managers and educators.

Observatory integration within commercial development projects

Scientists around the world struggle to obtain funding for even small observatory systems. The cost of observatory infrastructure, such as the platform and dedicated data/power transmission cables to shore, often constitutes the largest expense and greatly limits observatory capabilities. Networks for ecological monitoring of large spatial extension and complexity should seek help from industrial infrastructures. Offshore energy development projects (e.g., telecommunication cables, wind farms, tidal/current mills and oil/gas platforms) provide a unique opportunity for mankind to gain a 'Window into the Sea' if government and industry leaders have the foresight to integrate ocean observatory systems into offshore development design. It is hoped that current large scientific actions are being conceived at higher institutional levels to combine the two visions and design offshore energy systems that can provide both much needed green energy and also much needed ocean observatory systems. Incorporation of ecosystem observatory modules into commercial offshore energy structures would provide an unprecedented view of underwater life to scientists, fishers and the public. Such observatories could consist of single platforms in small energy projects, to hundreds of platforms in offshore wind farms.

The incorporation of ocean observatory modules into offshore functioning or decommissioning energy platforms, could provide significant ecological mitigation and greatly improve public acceptance of maritime activities development. Offshore energy development can provide platforms for many observatory modules and because power and data cables are a necessary part of the energy delivery system, scientists could have a fully functional data transfer network to shore already in place. We believe that any commercial offshore energy development should be required to allocate a percentage of its construction and maintenance costs towards stewardship of the local natural resources, including research and mitigation, where data are provided free to the public and institutions.

An important component of mitigation for offshore commercial development is the incorporation of long-term monitoring to foster advancement of marine science by providing scientists and the public access to marine habitats (i.e., the 'Window into the Sea'). Incorporation of commercial structures into ocean observatory module networks goes beyond traditionally minimal efforts to mitigate for direct and indirect impacts, into a vision of enhancing stewardship of marine ecosystems for the greater public good. The integration of this type of environmental stewardship into offshore energy programs and its promotion to the industry is farsighted. The advancement of scientific knowledge about offshore habitats will be a significant by-product of offshore development if it includes integrated ecosystem monitoring as part of a wider ocean observatory program. This will be a form of mitigation for any impacts (including impacts on human perception of the aesthetic value of the habitat) as well as providing improved positive public relations. We contend that if the need for ecological monitoring is fully understood by engineers and the offshore commercial industries and incorporated into system design from the beginning that environmental monitoring and mitigation costs will be found to be much more palatable.

Concluding remarks

The quantification of energy-carbon transfer and linkages among habitats distributed along a coenocline from terrestrial to deep-sea ecosystems are critical to resource management but are difficult to study synoptically. In this scenario, the potential impacts of a wide range of anthropogenic influences from pollution, harvesting, habitat disturbance and other factors on habitat linkages, and the marine ecosystem are still little understood. Undersea observatories have the potential to be used to monitor ecosystems at temporal and spatial scales never attained before. Unfortunately, current observatory systems are not adequately designed to collect data with sufficient spatial quantification for many fisheries and ecological applications, particularly over ecosystem and global scales. Moreover, limited efforts have been made to understand the influence of the observatory structure and its operations on the local habitats and the resulting potential measurement bias. These limitations are compounded by the complexity of user access to data from multiple observation instruments which are often collected over different time-spans and maintained separately. The utilization of observatories designed for time- and area-synchronized recording of data from multiple observation technologies is key to addressing these issues in order for ocean observatories to be applicable to fisheries and ecosystem management on regional and global scales.

Here, we propose a new concept for undersea observatories that addresses these limitations by combing fixed and mobile platforms capable of conducting multiple types of spatially-quantified and synoptic observations (such as physical, acoustic, optic, and chemical) with ‘living laboratory’ capabilities. The module design allows for quantification of organism abundance, density and biomass, as well as habitat mapping in the surrounding area. Monitoring can be scaled up from specific locations surrounding individual modules, to habitat-scale monitoring by clusters of modules, and ecosystem-level monitoring by networks of module clusters arranged in ridged geometric spatial configurations. We argue that the development of cyber infrastructure to support data collection, storage, maintenance, and fully integrated user access is equally important to the development of ecosystem-level observatories. Finally, we describe how observatories can be enhanced as ‘living laboratories’ through the incorporation of independent autonomous instruments, and ‘plug-and-play’ exchangeable experimental payload packages on the module satellite pods. Much of the technology hardware necessary to implement our design is currently available or require some advancements (360° coverage). In contrast, software development is still in early development. What is novel about our design, is how the technologies are deployed to obtain cross-referencing data that is spatially quantified. The high-cost of ocean observatories continues to hinder their wide-scale application, which can only partially be addressed by our concept of a highly standardized module design. Therefore, we call for the integration of observatories into commercial development projects in both inshore and offshore areas as a component of mandatory mitigation for ecological impacts of commercial development.

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References

ACT (Alliance for Coastal Technologies). 2007. Underwater Passive Acoustic Monitoring for Remote Regions. A workshop of research scientists, technology developers, and resource managers. Hawaii Institute of Marine Biology, Coconut Island, Hawaii, Feb. 7-9, 2007. *Alliance for Coastal Technologies* Ref. No. ACT-07-02.

Afonso, P., McGinty, N., Graça, G., Fontes, J., Inácio, M., Totland, A., & Menezes, G. 2014. Vertical migrations of a deep-sea fish and its prey. *PLoS ONE* **9**(5), e97884

Aguzzi, J., & Company, J.B. 2010. Chronobiology of deep-water decapod crustaceans on continental margins. *Advances in Marine Biology* **58**, 155-225.

Aguzzi, J., Company, J.B., Costa, C., Menesatti, P., Garcia, J.A., Bahamon, N., Puig, P., & Sardà, F. 2011a. Activity rhythms in the deep-sea: a chronobiological approach. *Frontiers in Bioscience-Landmark* **16**, 131-150.

Aguzzi, J., Manuél, A., Condal, F., Guillén, J., Nogueras, M., Del Río, J., Costa, C., Menesatti, P., Puig, P., Sardà, F., Toma, D., & Palanques, A. 2011b. The new SEAfloor OBservatory (OBSEA) for remote and long-term coastal ecosystem monitoring. *Sensors-Basel* **11**, 5850-5872.

Aguzzi, J., Company, J.B., Costa, C., Matabos, M., Azzurro, E., Mànuel, A., Menesatti, P., Sardà, F., Canals, M., Delory, E., Cline, D., Favali, P., Juniper, S.K., Furushima, Y., Fujiwara, Y., Chiesa, J.J., Marotta, L., & Priede, I.M. 2012. Challenges to assessment of benthic populations and biodiversity as a result of rhythmic behaviour: Video solutions from cabled observatories. *Oceanography and Marine Biology: An Annual Review* **50**, 235-286.

Aguzzi, J., Doya, C., Tecchio, S., De Leo, F.C., Azzurro, E., Costa, C., Sbragaglia, V., Del Río, J., Navarro, J., Ruhl, H.A., Company, J.B, Favali, P., Purser, A., Thomsen, L., & Catalán, I.A. 2015a. Coastal observatories for monitoring of fish behaviour and their responses to environmental changes. *Reviews in Fish Biology and Fisheries* **25**, 463-483.

Aguzzi, J., Sbragaglia, V., Tecchio, S., Navarro, J., & Company, J.B. 2015b. Rhythmic behaviour of marine benthopelagic species and the synchronous dynamics of benthic communities. *Deep-Sea Research I* **95**, 1-11.

Aguzzi, J., Fanelli, E., Ciuffardi, T., Schirone, A., Craig, G., & the NEMO Consortium. 2017. Inertial bioluminescence rhythms at the Central Mediterranean KM3NeT deep-sea neutrino telescope. *Scientific Reports* **7**, 44938.

Aguzzi, J., Thomsen, L., Chatizevangelou, D., Del Río, J., Company, J.B., Marini, S., Fanelli, E., Floeghel, S., Danovaro, R., Rountree, R., Juanes, F., & De Leo, F. 2019. High-tech networks of robotic platforms for the monitoring of deep-sea crustacean populations. *Environmental Science and Technology* **53(12)**, 6616-6631.

Alldredge, A.L., & Silver, M.W. 1988. Characteristics, dynamics and significance of marine snow. *Progress in Oceanography* **20**, 41-82.

Allken, V., Handegard, N.O., Rosen, S., Schreyeck, T., Mahiout, T., & Malde, K. 2018. Fish species identification using a convolutional neural network trained on synthetic data. *ICES Journal of Marine Science* **76(1)**, 342-349.

Audoly, C., Rousset, C., Baudin, E., & Folegot, T. 2016. AQUO Project. Research on solutions for the mitigation of shipping noise and its impact on marine fauna: Synthesis of guidelines. In *Proceedings of the 23rd International Congress on Sound Vibrations*. Athens (Greece).

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Mullor, R.S., André, M., Rousset, C., & Kellett, P. 2017. Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO Project. *Journal of Oceanic Engineering IEEE* **42**(2), 373-387.

Bahamon, N., Aguzzi, J., Bernardello, R., Ahumada-Sempoal, M.A., Puigdefabregas, J., Cateura, J., Muñoz, E., Velásquez, Z. & Cruzado, A. 2011. The new pelagic Operational Observatory of the Catalan Sea (OOCS) for the multisensor coordinated measurement of atmospheric and oceanographic conditions. *Sensors* **11**(12), 11251-11272.

Barnes, C., Best, M.M.R., Johnson, F.R., Pautet, L., & Pirenne, B. 2013. Challenges, Benefits, and opportunities in installing and operating cabled ocean observatories: perspectives from NEPTUNE Canada. *IEEE Journal of Oceanic Engineering* **38**(1), 144-157.

Blondeau-Patissier, D., Gower, J.F., Dekker, A.G., Phinn, S.R., & Brando, V.E. 2014. A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans. *Progress in Oceanography* **123**, 123-144.

Bonin, F., Burguera, A., & Oliver, G. 2011. Imaging systems for advanced underwater vehicles. *Journal of Maritime Research* **8.1**, 65-86.

Borgman, C.L., Wallis, J.C., & Enyedy, N. 2007. Little science confronts the data deluge: habitat ecology, embedded sensor networks, and digital libraries. *International Journal on Digital Libraries* **7**, 17-30.

Bosch, J., Istenič, K., Gracias, N., Garcia, R. & Ridao, P. 2019. Omnidirectional Multicamera Video Stitching Using Depth Maps. *IEEE Journal of Oceanic Engineering* doi: 10.1109/JOE.2019.2924276Buck, J.J., Bainbridge, S.J., Burger, E.F., Kraberg, A., Casari, M., Darroch, L., Del Rio Fernandes, J., Metfies, K., Delroy, E., Fischer, P. & Gardner, T. 2019. Ocean data product integration through innovation-The next level of data interoperability. *Frontiers in Marine Science* **6**, 1-19.

Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., & Fabres, J. 2006. Flushing submarine canyons. *Nature* 444(7117), 354.

Chaturvedi, K., & Kolbe, T.H. 2019. Towards establishing cross-platform interoperability for sensors in smart cities. *Sensors* **19**, 562. doi:10.3390/s19030562

Chatzievangelou, D., Aguzzi, J., Ongston, A., Suárez, A., & Thomsen, L. In review. Spatio-temporal monitoring of key deep-sea megafauna with Internet Operated crawlers as a tool for ecological status assessment. *Scientific Reports*.

Čolaković, A., & Hadžialić, M. 2018. Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues. *Computer Networks* **144**, 17-39.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37**, 35-46.

Corgnati, L., Marini, S., Mazzei, L., Ottaviani, E., Aliani, S., Conversi, A., & Griffa, A. 2016. Looking inside the Ocean: Toward an Autonomous Imaging System for Monitoring Gelatinous Zooplankton. *Sensors* **16**, 2124.

Danovaro, R., Aguzzi, J., Fanelli, E., Billet, D., Gjerde, K., Jamieson, A., Ramirez-Llodra, E, Smith, C.R., Snelgrove, P.V.R., Thomsen, L., & Van Dover, C. 2017. A new international ecosystem-based strategy for the global deep ocean. *Science* **355**, 452-454.

Deegan, L.A., Hughes, J.E., & Rountree, R.A. 2000. Salt marsh support of marine transient species. In *Concepts and Controversies in Tidal Marsh Ecology*, M. Weinstein, & D. Kreeger (eds). Boston, Massachusetts: Kluwer Academic Publishers, 333-365.

Dame, R.F., Chrzanowski, T.H., Bildstein, K., Kjerfue, B., McKellar, H., Nelson, D., Spurrier, J., Stancyk, S., Stevenson, L.H., Bernberg, J., & Zingmark, R. 1986. The outwelling hypothesis and North Inlet, South Carolina. *Marine Ecology Progress Series* **33**, 217-229.

Del Río, J., Toma, D.M., Martínez, E., O'Reilly, T.C., Delory, E., Pearlman, J.S., Waldmann, C., & Jirka, S. 2018. A Sensor Web Architecture for integrating smart oceanographic sensors into the semantic sensor Web. *IEEE Journal of Oceanic Engineering* **43**(4), 830-842.

De Leo, F., Ogata, B., Sastri, A., Heesemann, M., Mihály, S., Galbraith, M., & Morley, M.G. 2018. High-frequency observations from a deep-sea cabled observatory reveal seasonal overwintering of *Neocalanus* spp. in Barkley Canyon, NE Pacific: insights into particulate organic carbon flux. *Progress in Oceanography* **169**, 120-137.

Doya, C., Aguzzi, J., Pardo, M., Matabos, M., Company, J.B., Costa, C., & Milhaly, S. 2014. Diel behavioral rhythms in the sablefish (*Anoplopoma fimbria*) and other benthic species, as recorded by deep-sea cabled observatories in Barkley canyon (NEPTUNE-Canada). *Journal of Marine Systems* **130**, 69-78.

Durden, J.M., Schoening, T., Althaus, F., Friedman, A., Garcia, R., Glover, A.G., Greinert, J., Stout, N.J., Jones, D.O., Jordt, A., & Kaeli, J.W. 2016a. Perspectives in visual imaging for marine biology and ecology: from acquisition to understanding. *Oceanography and Marine Biology Annual Review* **54**, 1-72.

Durden, J.M., Bett, B.J., Horton, T., Serpell-Stevens, A., Morris, K.J., Billet, D.S.M., & Ruhl, H.A. 2016b. Improving the estimation of deep-sea megabenthos biomass: dimension to wet weight conversions for abyssal invertebrates. *Marine Ecology Progress Series* **552**, 71-79.

FAO (Food and Agriculture Organization of the United Nations). 2018. The State of Mediterranean and Black Sea Fisheries. General Fisheries Commission for the Mediterranean. Rome: FAO.

Fehlmann, G., & King, A.J. 2016. Bio-logging. *Current Biology* **26**, 830-831.

Florea, A.G., & Buiu, C. (eds.) 2017. *Membrane Computing for The Distributed Control of Robotic Swarms*. Advances in Computational Intelligence and Robotics (ACIR) Book Series. IGI Global.

Fujii, T., & Jamieson, A.J. 2016. Fine-scale monitoring of fish movements and multiple environmental parameters around a decommissioned offshore oil platform: A pilot study in the North Sea. *Ocean Engineering* **126**, 481-487.

Graeme, C.H., Ferreira, L.C., Sequeira, A.M.M., Meekan, M.G., Duarte, C.M., Bailey, H., Bailleul, F., Bowen, W.D., Caley, M.J., Costa, D.P., Eguíluz, V.E., Fossette, S., Friedlaender, A.S, Gales, N., Gleiss, A.C., Gunn, J., Harcourt, R., Hazen, E.L., Heithaus, M.R., Heupel, M., Holland, K., Horning, M., Jonsen, I., Kooyman, G.L., Lowe, C.L., Madsen, P.T., Marsh, H., Phillips, R.A., Righton, D., Ropert-Coudert, Y., Sato, K., Shaffer, S.A, Simpfendorfer, C.A., Sims, D.W., Skomal, G., Takahashi, A., Trathan, P.N., Wikelski, M., Womble, J.N., & Thums, M. 2010. Key questions in marine megafauna movement ecology. *Trends in Ecology and Evolution* **31**, 463-475.

Haines, E.B. 1979. Interactions between Georgia salt marshes and coastal waters: A changing paradigm. In *Ecological Processes in Coastal and Marine Systems* R.J. Livingston (ed) New York, New York: Plenum, 35-46.

Handegard, N.O., Du Buisson, L., Brehmer, P., Chalmers, S.J., De Robertis, A., Huse, G., Kloser, R., Macaulay, G., Maury, O., Ressler, P.H., & Stenseth, N.C. 2013. Towards an acoustic-based coupled observation and modelling system for monitoring and predicting ecosystem dynamics of the open ocean. *Fish and Fisheries* **14**(4), 605-615.

Harvey, E.S., & Shortis, M.R., 1998. Calibration stability of an underwater stereo-video system: implications for measurement accuracy and precision. *Marine Technology Society Journal* **32**(2), 3-17.

Honjo, S. 1980. Material fluxes and modes of sedimentation in the mesopelagic and bathypelagic zones. *Journal of Marine Research* **38**, 53-97.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Flemming, J.E.M., & Whoriskey, F.G. 2015. Aquatic animal telemetry: A panoramic window into the underwater world. *Science* **348**, 1221-1231.

Irigoien, X, Klevjer, T.A., Røstad, A., Martinez, U., Boyra, G., Acuña, J.L., Bode, A., Echevarria, F., Gonzalez-Gordillo, J.I., Hernandez-Leon, S., Agusti, S., Aksnes, D.L., Duarte, C.M., & Kaartvedt, S. 2014. Large mesopelagic fishes' biomass and trophic efficiency in the open ocean. *Nature* **5**, 3271.

Juanes, F. 2018. Visual and acoustic sensor for early detection of biological invasions: Current uses and future potential. *Journal for Nature Conservation* **42**, 7-11.

Juniper, S.K., Sastri, A., Mihály, S., Whitehead, J., Brent, E., Helmuth, T., & Miller, L. 2016. Continuous pCO2 time series from Ocean Networks Canada cabled observatories on the northeast Pacific shelf-edge/upper slope and in the sub-tidal Arctic. *European Geophysical Union, Geophysical Research Abstracts* **18**, EGU2016-9426.

Kobari, T., Steinberg, D.K., Ueda, A., Tsuda, A., Silver, M.W., & Kitamura, M. 2008. Impacts of ontogenetically migrating copepods on downward carbon flux in the western subarctic Pacific Ocean. *Deep-Sea Research II* **55**, 1648-660.

Lecours, V., Devillers, R., Schneider, D.C., Lucieer, V.L., Brown, C.J., & Edinger, E.N. 2015. Spatial scale and geographic context in benthic habitat mapping: review and future directions. *Marine Ecology Progress Series* **535**, 259-284.

Lin, Y., Hsiung, S.-C., Piersal, R., Whitem, C., Lowe, C.G., & Clark, C.M. 2016. A multi-autonomous underwater vehicle system for autonomous tracking of marine life. *Journal of Field Robotics* **34**, 757-774.

Lloyd, S., Lepper, P., & Pomeroy, S. 2017. Evaluation of UAVs as an underwater acoustics sensor deployment platform. *International Journal of Remote Sensing* **38**, 2808-2817.

Locascio, J., Mann, D., Wilcox, K., & Luther, M. 2018. Incorporation of acoustic sensors on a coastal ocean monitoring platform for measurements of biological activity. *Marine Technology Society Journal* **52**(3), 64-70.

Longhurst, A.R. 1976. Vertical migration. In *The Ecology of the Seas*, D.H. Cushing & J.J. Walsh (eds). Oxford: Blackwell Scientific Publications, 116-137.

Luczkovich, J.J., Mann, D.A., & Rountree, R.A. 2008. Passive acoustics as a tool in fisheries science. *Transactions of the American Fisheries Society* **137**, 533-541.

Marini, S., Corgnati, L., Manotovani, C., Bastianini, M., Ottaviani, E., Fanelli, E., Aguzzi, J., Griffa, A., & Poulain, P.M. 2018a. Automated estimate of fish abundance through the autonomous imaging device GUARD1. *Measurement* **126**, 72-75.

Marini, S., Fanelli, E., Sbragaglia, V., Azzurro, E., Del Rio, J. & Aguzzi, J. 2018b. Tracking fish abundance by underwater image recognition. *Scientific Reports* **8**, 13748.

Marshall, N.B. 1971. *Explorations in The Life of Fishes*. Cambridge, Massachusetts: Harvard University Press.

Marshall, K.N., Levin, P.S., Essington, T.E., Koehn, L.E., Anderson, L.G., Bundy, A., Carothers, C., Coleman, F., Gerber, L.R., Grabowski, J.H., & Houde, E. 2018. Ecosystem-based fisheries management for social–ecological systems: Renewing the focus in the United States with next generation fishery ecosystem plans. *Conservation Letters* **11**(1), e12367.

Martin, P., Remy, L., Theodoridou, M., Jeffery, K. & Zhao, Z., 2019. Mapping heterogeneous research infrastructure metadata into a unified catalogue for use in a generic virtual research environment. *Future Generation Computer Systems* **101**, 327-340.

Masmitja, I., Bouvet, P.J., Gomarítz, S., Aguzzi, J., & Del Río, J. 2017. Accuracy and precision studies for range-only underwater target tracking in shallow waters. 22nd IMEKO TC4 International Symposium and 20th International Workshop on ADC Modelling and Testing. Supporting World Development Through Electrical and Electronic Measurements. 14-15 September, 2017. Bucharest (Romania).

Mauchline, J. 1980. The biology of mysids and euphausiids. Part 2. The biology of euphausiids. *Advances in Marine Biology* **18**, 372-623.

Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe, D.K., Fossette, S., Hobday, A.J., Bennett, M., Benson, S., Caldwell, M.R., Costa, D.P., Dewar, H., Eguchi, T., Hazen, L., Kohin, S., Sippel, T., & Crowder, L.B. 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy* **58**, 42-50.

McCave, I.N. 1975. Vertical flux of carbon in the ocean. *Deep-Sea Research* **22**, 491-502.

Merrett, N.R. 1978. On the identity and pelagic occurrence of larval and juvenile stages of rattail fishes (family Macrouridae) from 60°N,20°W and 53°N,20°W. *Deep-Sea Research I* **25**, 147-160.

Merritt, D, Donovan, M.K., Kelley, C., Waterhouse, L., Parke, M., Wong, K., & Drazen, J.C. 2011. BotCam: a baited camera system for nonextractive monitoring of bottomfish species. *Fishery Bulletin* **109**(1), 56-67.

Michener, W.K., & Jones, M.B. 2012. Ecoinformatics: Supporting ecology as a data-intensive science. *Trends in Ecology and Evolution* **27**, 85-93.

Moll, R.J., Millspaugh, J.J., Beringer, J., Sartwell, J., & He, Z. 2007. A new 'view' of ecology and conservation through animal-borne video systems. *Trends in Ecology and Evolution* **22**, 660-668.

Morris, C, Andreetto, P, Banci, L, Bonvin, AM, Chojnowski, G, del Cano, L, Carazo, JM, Conesa, P, Daenke, S, Damaskos, G, & Giachetti, A. West-Life: A Virtual Research Environment for structural biology. *Journal of Structural Biology*: **X**. 2019 Jan 1;1:100006. https://doi.org/10.1016/j.yjsbx.2019.100006

Mouy, X., Rountree, R., Juanes, F., & Dosso, S.E. 2018. Cataloguing fish sounds in the wild using combined acoustic and video recordings. *The Journal of the Acoustical Society of America* **143**(5), 333-339.

Nassar, J.M., Khan, S.M., Velling, S.J., Diaz-Gaxiola, A., Shaikh, S.F., Geraldi, N.R., Sevilla, G.A.T., Duarte, C.M. & Hussain, M.M., 2018. Compliant lightweight non-invasive standalone "Marine Skin" tagging system. *npj Flexible Electronics* **2**(1), 13, doi: 10.1038/s41528-018-0025-1

Naylor, E. 2010. *Chronobiology of Marine Organisms*. Cambridge: Cambridge University Press.

Nelson, J.R., & Weisberg, R.H. 2008. *In situ* observations and satellite remote sensing in SEACOOS: Program development and lessons learned. *Marine Technology Society Journal* **42**(3), 41-54.

Nixon, S.W. 1980. Between coastal marshes and coastal waters: A review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In *Estuarine and Wetland Processes*, P. Hamilton & K.B. MacDonald (eds.). New York, New York: Plenum, 437-525

NOC (National Ocean Council). 2016. *Animal Telemetry Network Implementation Plan 2016-2021*. Printed in the United States of America, December 19, 2016.

OBSEA. 2019. The OBSEA underwater observatory. https://obsea.es/ (accessed 18 April 2019).

Odum, E.P. 1980. The status of three ecosystems: Level hypotheses regarding salt marsh estuaries: tidal subsidy, outwelling, and detritus-based food chains. In *Estuarine Perspectives*, V.S. Kennedy (ed). New York, New York: Academic Press, 485-495.

Odum, H.T. 1996. *Environmental Accounting: Energy and Environmental Decision Making*. New York, New York: Wiley.

ONC (Ocean Networks Canada). 2019. Discover the Ocean. Understand the Planet. http://www.oceannetworks.ca/sights-sounds/images/maps (accessed 18 April 2019).

OOI (Ocean Observatories Initiative). 2019. *The Ocean Observatories Initiative*. https://oceanobservatories.org/ (accessed 18 April 2019).

OTN (Ocean Tracking Network).2019. http://oceantrackingnetwork.org/ (accessed 18 April 2019).

Pearlman, J.S., Bushnell, M., Coppola, L., Buttigieg, P.L., Pearlman, F., Simpson, P., Barbier, M., Karstensen, J., Muller-Karger, F.E., Munoz-Mas, C. & Pissierssens, P., 2019.

Evolving and sustaining ocean best practices and standards for the next decade. *Frontiers in Marine Science* **6**, 277.

Pirenne, B., Guillemot, E., Hoeberechts, M. Jenkyns, R., Morley, M.G., Rees, G., & Dewey, R.K. 2018. Oceans 2.0: A platform to exploit earth and ocean science data. American Geophysical Union Annual Meeting, San Francisco, California.

Pomeroy, L.R., & Wiegert, R.G. (eds) 1981. *The Ecology of a Salt Marsh*. New York, New York: Springer-Verlang Inc.

Puig, P., Palanques, A., & Martín, J. 2014. Contemporary sediment-transport processes in submarine canyons. *Annual Review of Marine Science* **6**, 53-77.

Qin, Y., Sheng, Q.Z., Falkner, N.J.G., Dustdar, S., Wang, H., & Vasilakos, A.V. 2016. When things matter: A survey on data-centric internet of things. *Journal of Network and Computer Applications* **64**, 137-153.

Recknagel, F., & Michener, W.K. (eds.) 2017. *Ecological Informatics: Data Management and Knowledge Discovery*. Springer.

Rempel, A. & Cabrera, D.A. 2018. *The Oceans 2.0 Sandbox*. https://wiki.oceannetworks.ca/display/O2A/The+Oceans+2.0+Sandbox (accessed 18 April 2019).

Rex, M.A., & Etter, R.J. (eds) 2010. *Deep-Sea Biodiversity: Pattern and Scale*. Cambridge, Massachusetts: Harvard University Press.

Rogers, A.D. 2015. Environmental change in the deep ocean. *Annual Review of Environment and Resources* **40**, 1-38.

Rotllant, G., Aguzzi, J., Sarria, D., Gisbert, E., Sbragaglia, V., Del Río, J., Simeó, C.G., Mànuel, A., Molino, E., Costa, C., & Sardà, F. 2014. Pilot acoustic tracking study on adult spiny lobsters (*Palinurus mauritanicus*) and spider crabs (*Maja squinado*) within an artificial reef. *Hydrobiologia* **742**, 27-38.

Rountree, R.A. 1992. *Fish and macroinvertebrate community structure and habitat use patterns in salt marsh creeks of southern New Jersey, with a discussion of marsh carbon export*. Ph.D. Dissertation, Rutgers, The State University of New Jersey. New Brunswick. U.M.I. #DAI-9232951.

Rountree, R.A., Perkins, P.J., Kenney, R.D., & Hinga, K.R. 2002. Sounds of Western North Atlantic Fishes: Data rescue. *Bioacoustics* **12**, 242–244.

Rountree, R.A., Goudey, C., & Hawkins, T. (eds.) 2003. *Listening to Fish: Proceedings of the International Workshop on the Applications of Passive Acoustics to Fisheries*. April 8-10, 2002. Dedham, MA. MIT Sea Grant Technical Report MITSG 03-2. On line version at: http://web.mit.edu/seagrant/aqua/cfer/acoustics/PAprocBrFINAL.pdf

Rountree, R.A. 2008. Do you hear what I hear? Future technological development and needs in passive acoustics underwater observation. *Marine Technology Reporter* **51**(9), 40-46.

Rountree, R.A., & Able, K.W. 2007. Spatial and temporal habitat use patterns for salt marsh nekton: Implications for functions. *Aquatic Ecology* **41**, 25-45.

Rountree, R.A., Gilmore, R.G., Goudey, C.A, Hawkins, A.D., Luczkovich, J., & Mann, D.A. 2006. Listening to Fish: Applications of Passive Acoustics to Fisheries Science. *Fisheries* **31**(9), 433-446

Rountree, R.A., & Juanes, F. 2010. First attempt to use a remotely operated vehicle to observe soniferous fish behaviour in the Gulf of Maine, Western Atlantic Ocean. *Current Zoology* **56**(1), 90-99.

Rountree, R.A., Juanes, F., Goudey, C.A., & Ekstrom, K.E. 2012. Is biological sound production important in the deep sea? In *The Effects of Noise on Aquatic Life*, A.N. Popper & A. Hawkins (eds.) New York, New York: Springer Science+Business Media, LLC, 118-183 doi: 10.1007/978-1-4419-7311-5_41. 181-183

Rountree, R.A., Juanes, F., & Bolgan, M. 2018. Air movement sound production by alewife, white sucker, and four salmonid fishes suggests the phenomenon is widespread among freshwater fishes. *PLoS ONE* **13**(9), e0204247

Santos, A.M.P. 2000. Fisheries oceanography using satellite and airborne remote sensing methods: A review. *Fisheries Research* **49**(1), 1-20.

Sato, M., Dower, J.F., Kunze, E., & Dewey, R. 2013. Second-order seasonal variability in diel vertical migration timing of euphausiids in a coastal inlet. *Marine Ecology Progress Series* **480**, 39-56.

Seabrook, S., De Leo, F.C., & Thurber, A. 2019. Flipping for food: the use of a methane seep by tanner crabs (*Chionoecetes tanneri*). *Frontiers in Marine Science* 6, 43. https://doi.org/10.3389/fmars.2019.00043

Shenoi, R.A., Bowker, J.A., Dzielendziak, A.S., Lidtke, A.K., Zhu, G., Cheng, F., Argyos, D., Fang, I., Gonzalez, J., Johnson, S., Ross, K., Kennedy, I., O'Dell, M., & Westgarth, R. 2015. Global marine technology trends 2030. Lloyd's Register, QinetiQ and the University of Southampton. https://issuu.com/lr_marine/docs/55046_lr2030_web-lr_25mb/190 (accessed 18 April 2019)

Shortis, M., & Abdo, E.H.D. 2016. A review of underwater stereo-image measurement for marine biology and ecology applications. *Oceanography and Marine Biology: An Annual Review* **47**, 257-292.

Shortis, M.R., Seager, J.W., Williams, A., Barker, B.A., & Sherlock, M. 2008. Using stereo-video for deep water benthic habitat surveys. *Marine Technology Society Journal* **42**(4), 28-37.

Sivčev, S., Coleman, J., Omerdić, E., Dooly, G. & Toal, D. 2018. Underwater manipulators: A review. *Ocean Engineering* **163**, 431-450.

Skiena, S.S. 2017. *The Data Science Design Manual*. Springer Publishing Company, Incorporated.

Teal, J.M. 1962. Energy flow in the salt marsh ecosystem of Georgia. *Ecology* **43**, 614-624.

Thomsen, L., Aguzzi, J., Costa, C., De Leo, F., Ogston, A., & Purser, A. 2017. The oceanic biological pump: rapid carbon transfer to depth at continental margins during winter. *Scientific Reports* **7**(1), 10763.

Toonen, H.M., & Bush, S.R. 2018. The digital frontiers of fisheries governance: fish attraction devices, drones and satellites. *Journal of Environmental Policy and Planning*, doi: 10.1080/1523908X.2018.1461084

Tuck, I.D., Parsons, D.M., Hartill, B.W., & Chiswell, S.M. 2015. Scampi (*Metanephrops challengeri*) emergence patterns and catchability. *ICES Journal of Marine Science* **72**, 199-210.

Tunnicliffe, V., Dewey, R., & Smith, D. 2003. Research Plans for a Mid-Depth Cabled Seafloor Observatory in Western Canada. *Oceanography* **16**(4), 53-59.

Vetger, A.C., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M.L., Costa, M. F., Eriksen, M., Eriksson, C., Estrades, A., Gilardi, K.V.K., Hardesty, B.D., Ivar do Sul, J.A., Lavers, J.L., Lazar, B., Lebreton, L., Nichols, W.J., Ribic, C.A., Ryan, P.G., Schuyler, Q.A., Smith, S.D.A., Takada, H., Townsend, K.A., Wabnitz, C.C.C. Wilcox, C., Young, L.C., & Hamann, M. 2014. Global research priorities to mitigate plastic pollution impacts on marine wildlife. *Endangered Species Research* **25**, 225–247.

Vinogradov, M.E. 1953. The role of vertical migration of the zooplankton in the feeding of deep sea animals. *Priroda* **6**, 95-96.

Vinogradov, M.E. 1955. Vertical migrations of zooplankton and their importance for the nutrition of abyssal pelagic faunas. *Transactions of the Institute of Oceanology (USSR)* **13**, 71-76.

Vinogradov, M.E. (ed) 1971. Life activity of pelagic communities in the ocean tropics (Based on Data of the 44th Cruise of the R/V Vityaz). Institute of Oceanography, Academy of Science of the USSR. Izdatel'stvo "Nauka." Moskva. (Kaner, N., Transl., 1973. Israel Program for Scientific Translations, Jerusalem).

Wakefield, W.W., & Smith, K.L. Jr. 1990. Ontogenetic vertical migration in *Sebastolobus altivelis* as a mechanism for transport of particulate organic matter at continental slope depths. *Limnology and Oceanography* **35**(6), 1314-1328.

Wall, C.C., Rountree, R.A., Pomerleau, C., & Juanes, F. 2013. An exploration for deep-sea fish sounds off Vancouver Island from the NEPTUNE Canada ocean observing system. *Deep-Sea Research I* **83**, 57-64.

Walters, C.C. 2007. Is adaptive management helping to solve fisheries problems? *AMBIO: A Journal of the Human Environment* **36**(4), 304-308.

Williams, K., Rooper, C.N., & Towler, R. 2010. Use of stereo camera systems for assessment of rockfish abundance in untrawlable areas and for recording pollock behavior during midwater trawls. *Fishery Bulletin* **108**(3), 352-62.

Williams, K., Rooper, C.N., De Robertis, A., Levine, M. & Towler, R. 2018. A method for computing volumetric fish density using stereo cameras. *Journal of Experimental Marine Biology and Ecology* **508**, 21-26.

Wilmer, C.C., Nickel, B., Bryce, C.M., Smith, J.A., Wheat, R.E., & Yovovich, V. 2015. The golden age of bio-logging: How animal-borne sensors are advancing the frontiers of ecology. *Ecology* **96**, 1741-1753.

Zeppilli, D., Pusceddu, A., Trincardi, F., & Danovaro, R. 2016. Seafloor heterogeneity influences the biodiversity–ecosystem functioning relationships in the deep sea. *Scientific Reports* **6**, 26352.

Table 1. Optoacoustic-image and passive acoustic sensors installed on the standard cabled ecosystem observatory module and its associated mobile docked platforms.

Components	Instruments	Purpose
Central node	Multiple	Module power supply, data deposition and transmission, instrument platform, and mobile dockage platform.
	Hydrophones	Passive acoustic monitoring including recording of environmental noise, system noise, and biological sounds over the biologically relevant frequency range of 1 Hz to 150 kHz. Component of the module's 3-dimensional passive acoustic array for sound source location; cross-reference with video, acoustic imaging sonar, and echosounder for species identification, tracking and target strength quantification.
	Stereo-video cameras	Video recording of conditions and organisms over 360° around the central node to determine the size and spatial location of individual organisms. Use for identifying or confirming the source of sounds, targets in the acoustic image, and bioacoustic echosounder targets.
	Pan-tilt HD cameras	User controlled video cameras with pan-tilt control, zoom capability and lighting control, for use in investigating selected field of view areas, infrastructure elements, and to zoom in on selected passive acoustic, acoustic image, and echosounder targets for identification and behavioral observations.
	Acoustic imaging sonar cameras	Recording the presence and movements of animals in a 360° cylindrical area surrounding the central node during all visibility conditions; cross-reference with passive acoustic array source location, stereo cameras location, pan-tilt cameras, and echosounder targets for species identification, tracking and target strength quantification.
	Rotary horizontal multi-beam echosounder	Bioacoustic echosounder to quantify distribution of organism in the water column within a 360° zone surrounding the central node and extending outward for a radius of 100 – 800 m. Cross-reference with passive acoustic array source location, stereo camera localization, and pan-tilt cameras, for species identification, tracking and target strength quantification.
	Environmental sensor package	Continuous recording of habitat variables; e.g., pressure, temperature, salinity, current speed and direction, methane, oxygen, nitrates, Ph, chlorophyll and turbidity.

	Acoustic and optic receivers and transponders	Acoustic receivers for animal and instrument borne telemetry signals. Also including receivers for acoustic modem-based or optical communication and data transmission. In some cases, transponders can be used for two-way communication with animal and instrument borne devices.
	Crawler and dockage	Placing and servicing autonomous devices and satellite experimental payloads; conduct physical and biological sampling in the area surrounding central node along fixed and pre-determined tracks.
	ROV and dockage	Central node servicing, place and service autonomous devices and satellite experimental payloads, conduct physical and biological sampling in area surrounding node, conduct video transect surveys, document fouling organism and species associations with infrastructure, investigate unknown targets detected by observation technologies.
	AUV and dockage	Conduct benthic habitat and biota distribution mapping transects around the central node and throughout area between modules within an observatory cluster. Investigate unknown echosounder targets beyond the range the Crawler and ROV and of video and acoustic imaging sonar ranges.
Satellite pods	Hydrophones	Passive acoustic recording of ambient sounds (see above). Components of the module's passive acoustic array for sound localization.
	Stereo-video cameras	360° calibrated visual recording of organisms (see above) around the satellite and cross reference with observational data from the central node.
	Pan-tilt video cameras	User controlled video cameras (see above). Also, to supplement and cross-reference observational data from the central node instruments.
	Environmental sensors	Record micro-distribution of physical parameters (see above) expected to vary within the module area.

	Experiment or observation payload	Exchangeable “plug-and-play” payload containing instruments for user-designed data collection or experimentation, such as settlement trays with different substrates (e.g., carbon, wood or bones and even litter), experimentation on light effect on species, tagging, etc.
Autonomous devices	Mission-dependent	Stand-alone sound recorders, cameras, cages, mesocosms, and other devices to be placed by ROV or Crawler to monitor short- and long-term conditions at a specific location such as monitoring a fish nest or sessile invertebrates. Other possible devices include animal collection traps and stand-alone small-scale experimental packages.

Figure legends

Figure 1. Example of some major linkages among habitats distributed along horizontal and vertical coenoclines connecting terrestrial to deep-sea ecosystems along a large river system. Major linkages are provided by a chain-of-migration connecting habitats horizontally, while a ladder-of-migration connects vertical habitats through ontogenetic and cyclical movements of organisms (see **Figure 2**). Other mechanisms of linkage include: (A) run-off from land to sea; (B) nutrient, detritus and organism 'outwelling', and corresponding 'inwelling' and (C) upwelling/downwelling occur largely due to water movements such as tides and storms; (D) deposition occurs where water velocity slows to allow precipitation of suspended materials, and entrapment and mortality of organisms, as well as fecal deposition of migrating organism; and finally, (E) organic and inorganic rain.

Figure 2. Example of mechanisms of energetic linkages among adjacent habitats or ecosystems through the distribution and movements of organisms. Major mechanisms include diffusion, ontogenetic migration, and chain-of-migration. Diffusion results from trophic transfer of energy among overlapping assemblages and is poorly understood. Ontogenetic migration results from movements of organisms among habitats as they grow and can be size, environmental condition (such as temperature), or seasonally mediated. The chain-of-migration (and analogous ladder-of-migration) results from rhythmic movements of organisms among habitats on seasonal, lunar, diel or tidal cycles. The smallest links in the chain are between adjacent habitats, but links from direct movements of organisms can occur on any spatial scale among habitats located along the same coenocline. Major mechanisms of energy transfer include predator-prey interactions, spawning, fecal deposition, and local mortality.

Figure 3. Schematic illustration of the proposed standard ecosystem observatory module consisting of a central node, 3 satellites, AUV, ROV and Crawler mobile platforms and their dockage, and various autonomous devices. Hydrophones on the central node and each satellite form a 3-dimensional passive acoustic array. Crawlers would operate on predetermined tracks lines to reduce their impact on the substrate.

Figure 4. Schematic 3-dimensional illustration (not to scale) of the spatial configuration of the central node and satellites of a module, and the overlap among video, acoustic imaging sonar, and echosounder spatial coverage areas (inset provides a birds-eye-view of the spatial configuration). Integration of multiple 3-dimensional observation modalities in a module provides cross-referencing data to identify and track organisms. (1-6) a single individual of species A is tracked as it moves through the module area. Changes in echosounder target strength due to orientation changes can be quantified by comparison of different observations at each location, enhancing our ability to determine fish identification from target strength data. (1) silent individual detected by echosounder and acoustic imaging sonar, provides target strength, orientation, location, and size estimates. (2) same individual produces sound loud enough to be localized by the passive acoustic array, actual location and identification confirmed by stereo-video, acoustic image and echosounder. Sound received level can then be corrected for exact location to obtain sound source level and detection range. (3) now silent it is detected by stereo video, acoustic imaging sonar, and echosounder from the central node, as well as stereo-video from a satellite. (4) the individual moves out of camera range but continues to be tracked by acoustic imaging sonar and echosounder, 5) as the individual leaves the module area it continues

to be tracked by echosounder. 6) separate individual of species A is detected on echosounder only, but target strength consistency of species A at other locations permits accurate attribution to species within the wider area covered by the echosounder. 7) A second unknown species is detected by acoustic imaging sonar and echosounder and is identified based on localization on a known sound. 8) the reaction of multiple fish of species C to light is quantified by acoustic imaging sonar and echosounder.

Figure 5. Schematic of an ecosystem observatory module enhanced with a pelagic satellite composed of a surface buoy and associated instruments to monitor vertical distribution of organisms and physical properties. The surface buoy would be equipped with downward-looking video camera, acoustic imaging sonar system and echosounder similar to those deployed on the benthic module components. It would also include a microphone and 360° video to capture above water audio and video data of weather and shipping conditions for correlation with underwater recordings. The mooring line would be variously equipped with monitoring instruments at different depths, and a cargo elevator system to transport materials, such as new scientific payloads for satellite nodes, between benthic and surface systems. The pelagic satellite includes a drone system to map aerial (e.g., birds) and aquatic megafauna (mammals, fish, turtles), as well as neustonic and pleustonic organisms and pollutants. Drones can also be used to carry an instrument payload such as a hydrophone or fluorometer and other instrumentation for spatial mapping.

Figure 6. Schematic illustration of an ecosystem observatory module cluster designed to provide synoptic data on differing spatial scales within the cluster area. Three or more modules should be

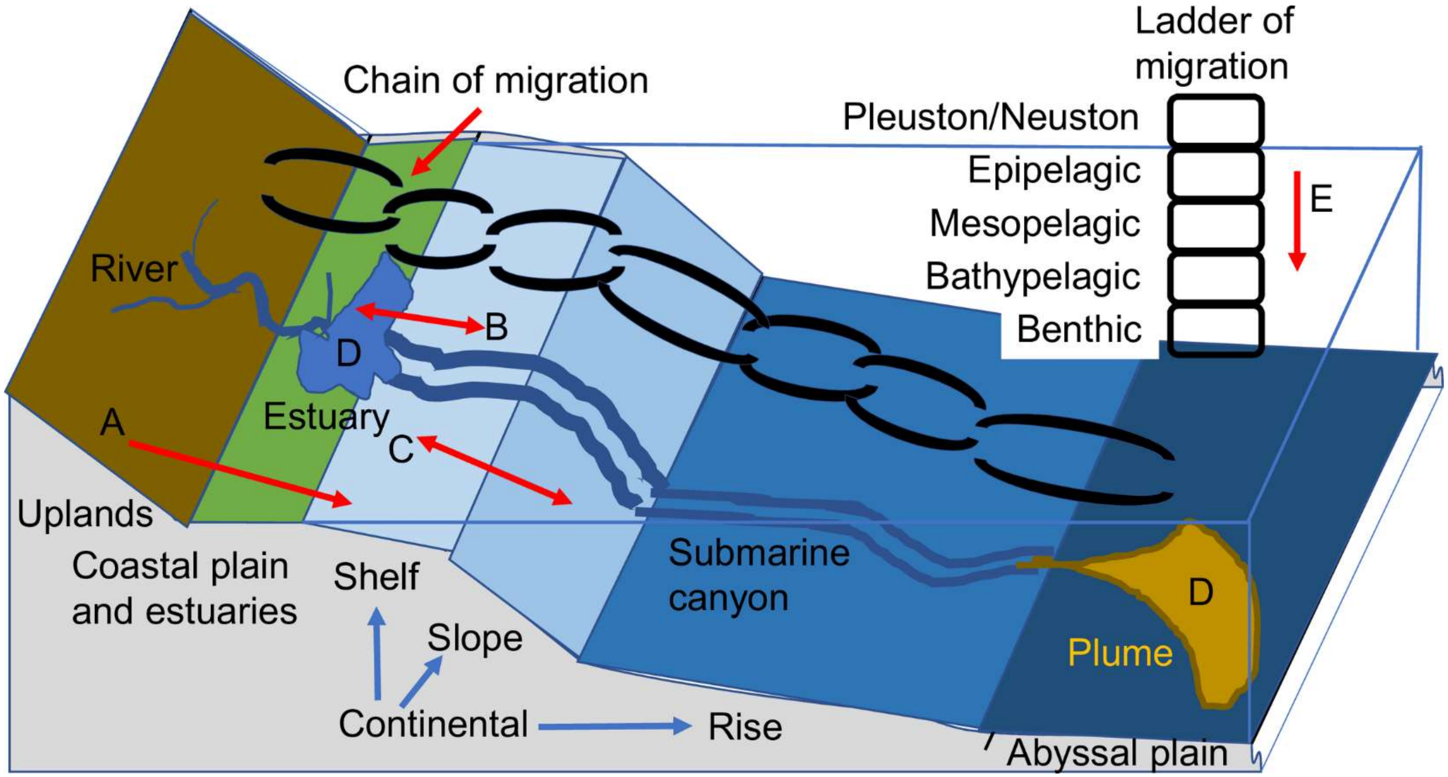
arranged in geometric clusters to allow detailed spatial comparisons within a larger spatial array. Spacing between modules is dependent on local conditions, AUV range, and optimal echosounder coverage. Clusters with module spacing allowing for overlap among bioacoustics echosounders, with greatest overlap in the center of the cluster, enable highly accurate identification of water column organisms over a large spatial area. One or more AUVs would be designed to navigate among modules in the cluster to map habitat and organism distributions within the cluster area, and provide additional ground-truth data for organism identification based on their target strength. Demersal and benthic organism and habitat mapping resolution is greatest around the modules, but is also high within the wider area encompassed by the observatory module cluster.

Figure 7. Sentinel ecosystem observatory networks (not to scale) composed of multiple module clusters distributed across a habitat gradient or coenocline occurring form estuarine/riverine areas to coastal zones and the shelf, down to the deep-continental margin of the slope and abyssal plain.

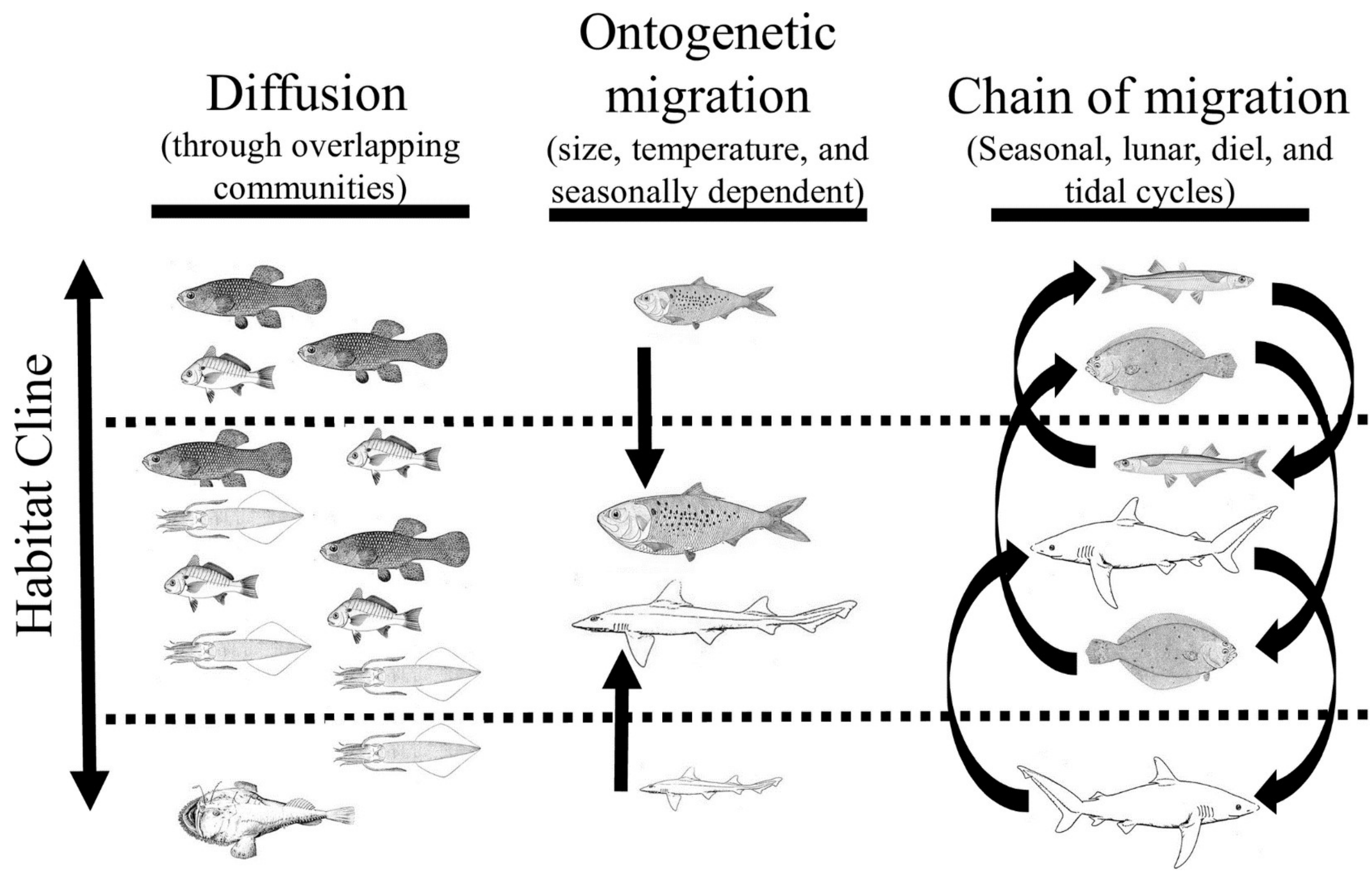
Figure 8. Hypothetical user interface of data from an ecosystem observatory module, composed of the central node plus the three satellites. All data windows (A-E) play in time simultaneously as indicated by the time cursor in the scientific data and passive acoustic sound windows (D-E). Video, acoustic image, and echosounder displays show only the portion of the 360° area surrounding the module which has been selected by the user with the angular view selection bar common to all three (below C). However, when the play is paused in time, the user can simultaneously scroll through all 360° surrounding the module in the video, acoustic image and echosounder windows (A-C). The overlapping observation modalities and integrated visual

displays are a powerful tool for examining correspondences among environmental conditions, observatory operations, and animal behavior. When autodetection is available for one or more of the observation technologies, the user can validate detections in other windows, for example targets ‘a-d’ are detected in video (A), acoustic image (B), and echosounder data (C). Data from each instrument can then be compiled to provide the most accurate information on species identification, 3-dimensional location, size and target strength together with environmental conditions at the time of detection. In addition, sound source targets localized by the passive acoustic array and shown in the sound window (sound labeled ‘d’ in E), can be identified by its corresponding location in the other windows (A-C).

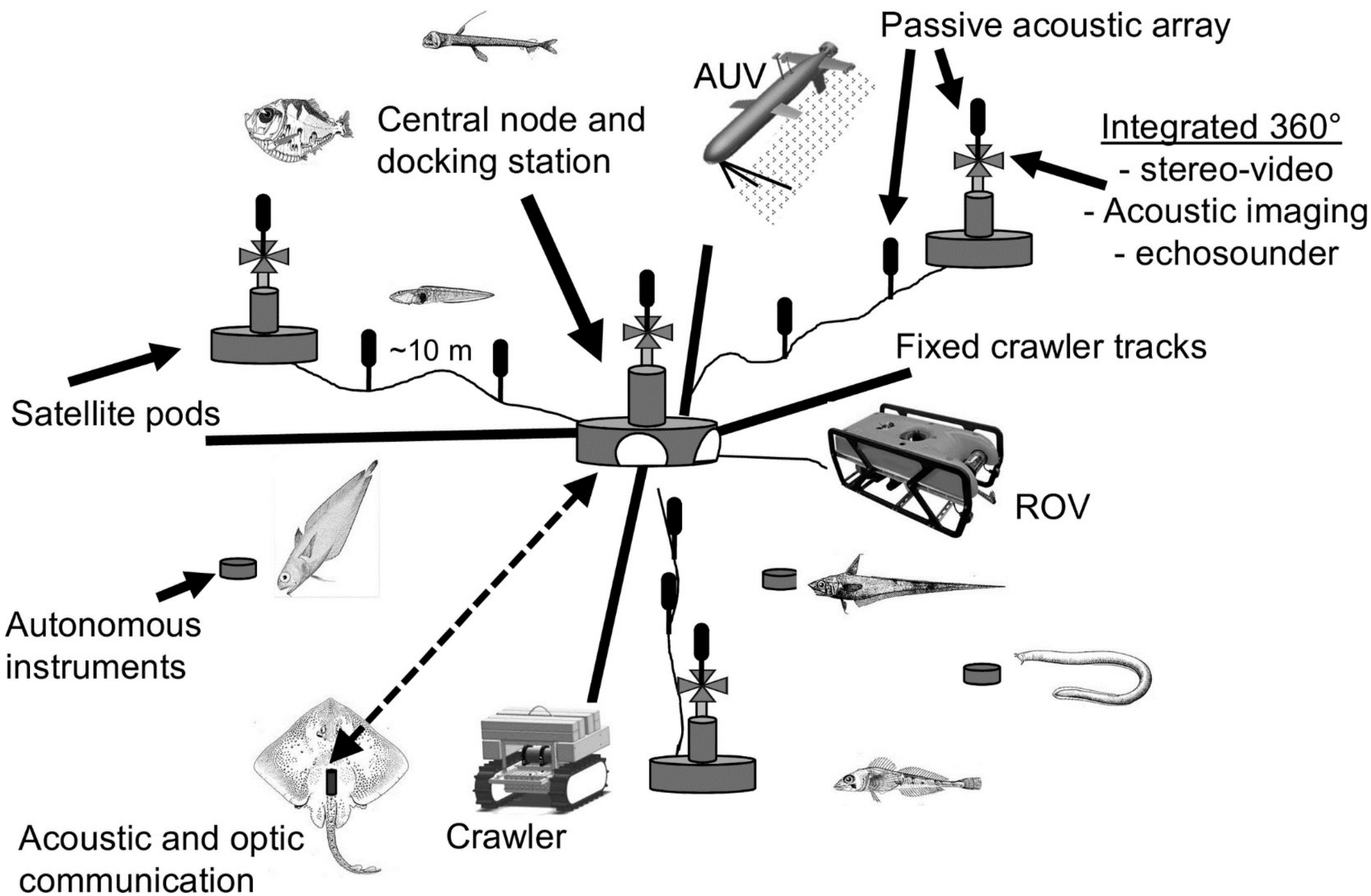
Rountree et al Fig. 1



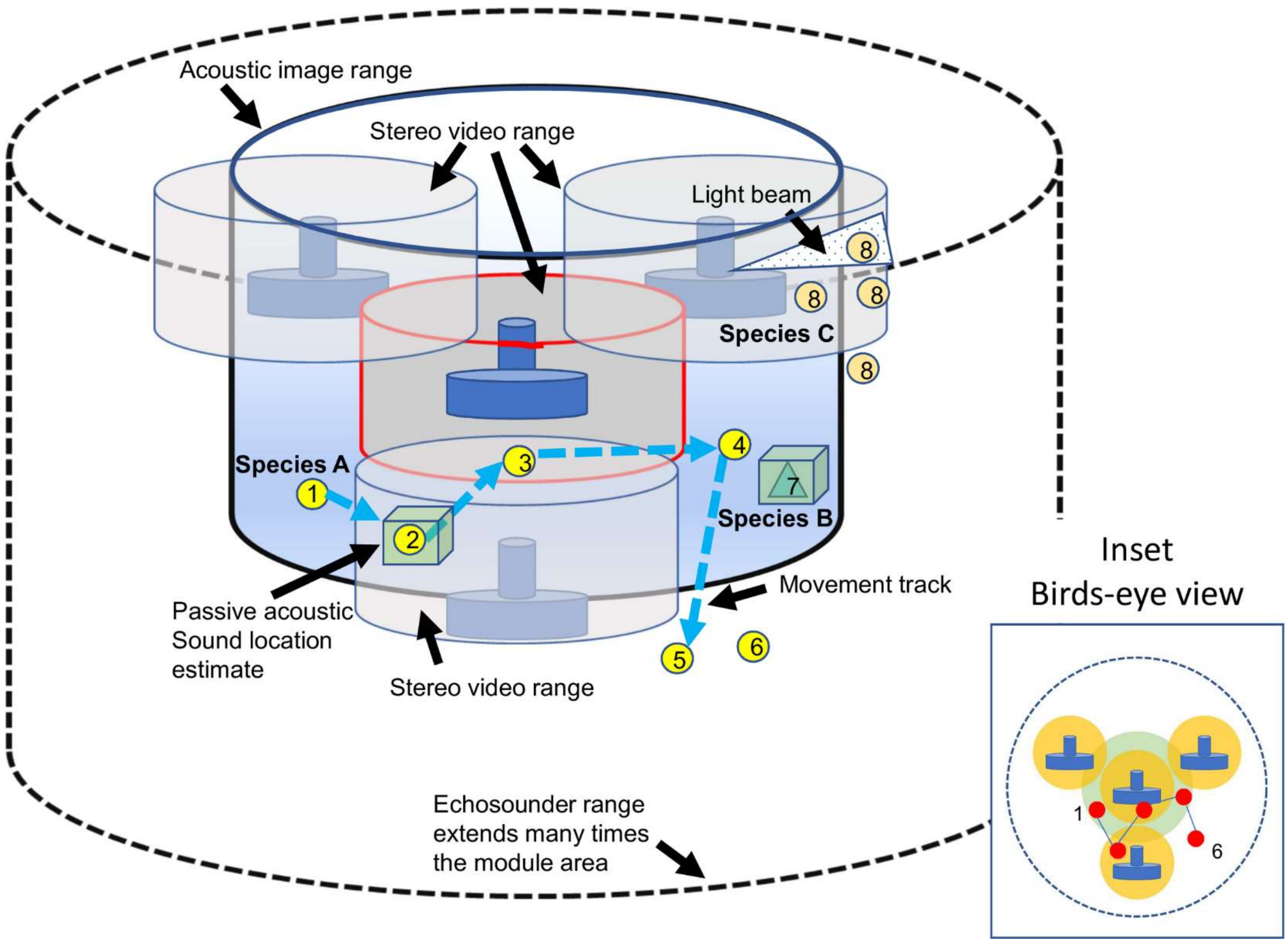
Rountree et al Fig. 2



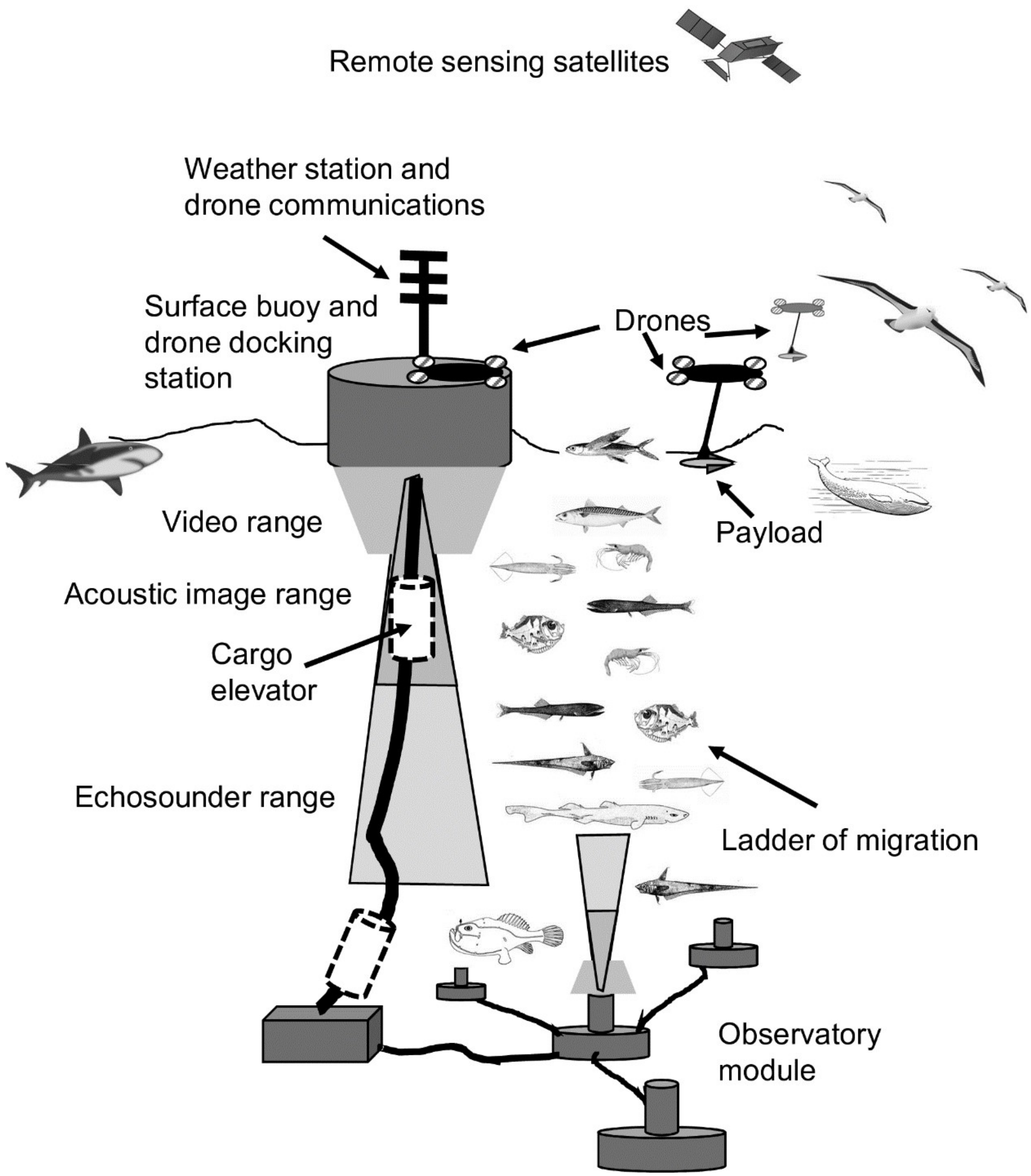
Rountree et al Fig. 3



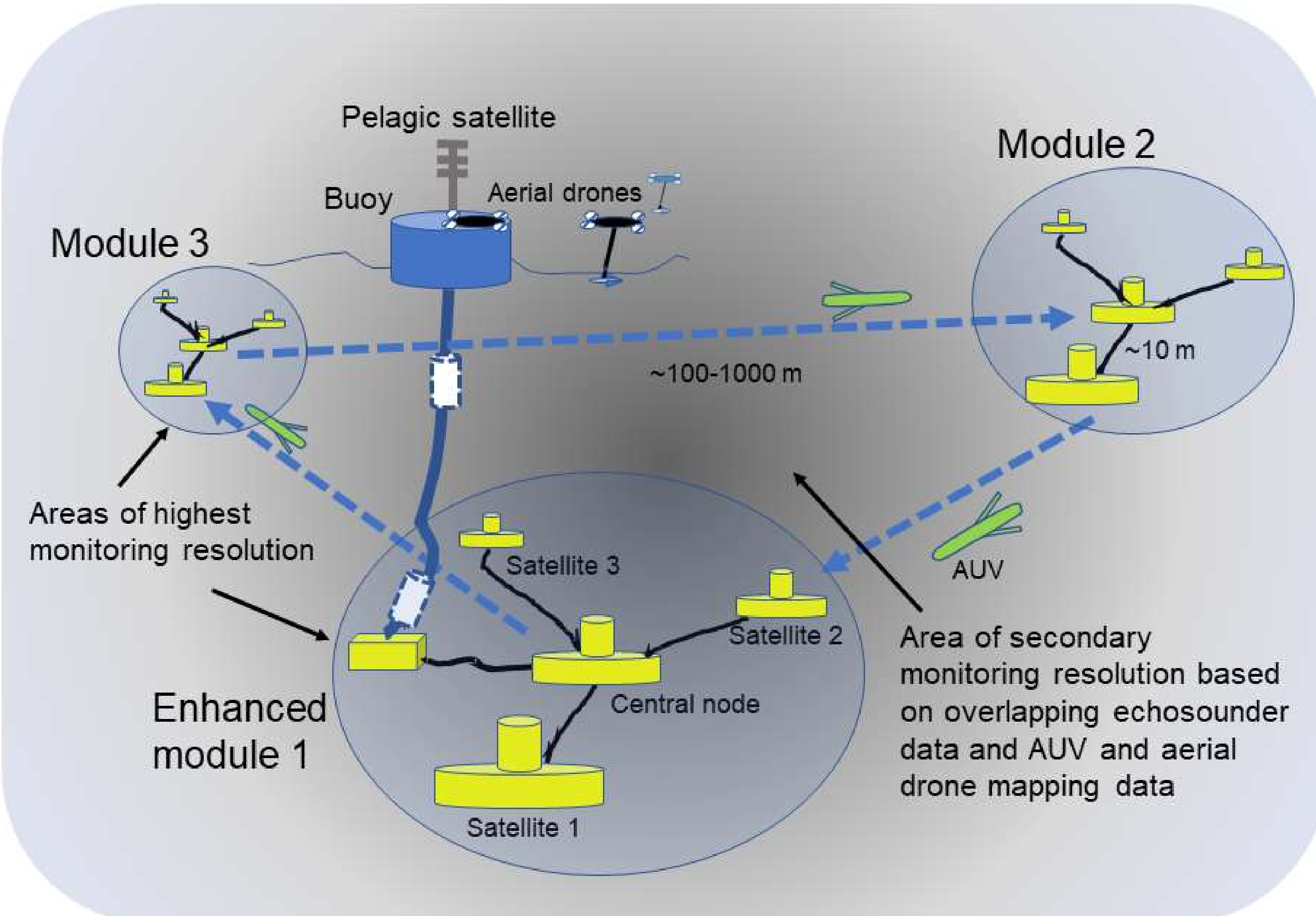
Rountree et al Fig. 4



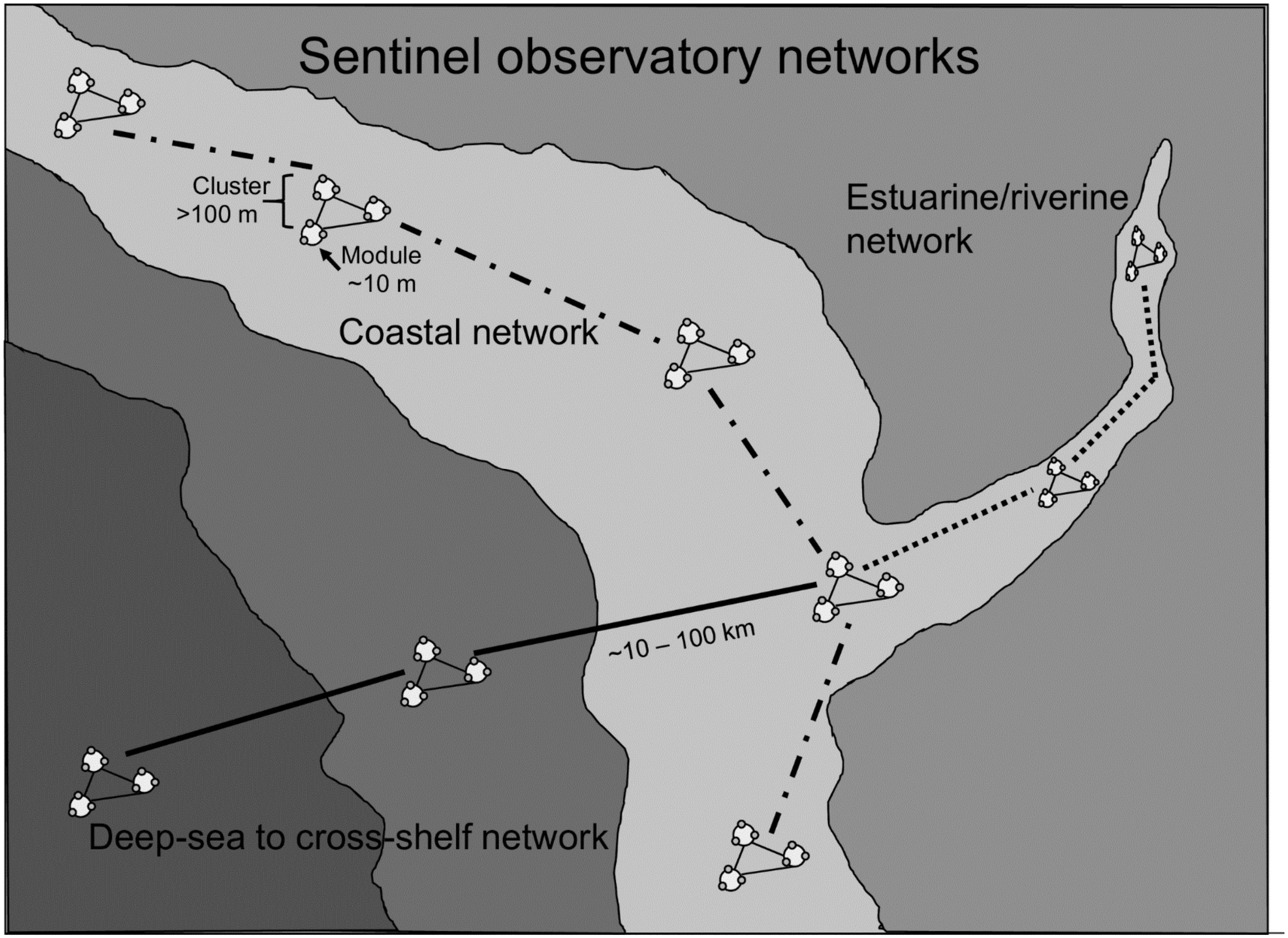
Rountree et al. Fig. 5



Rountree et al. Fig. 6



Rountree et al. Fig. 7



Rountree et al. Fig. 8 (placeholder)