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Towards a distributed and operational pelagic imaging network

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ABSTRACT

Dimensions of particulate matter found in the water column of marine and freshwater environments (the pelagic realm) range from nanometers to tens of meters. Included in this enormous size range are miniature bacteria, phytoplankton (photosynthetic microalgae), mixoplankton (mixotrophic microorganisms), micro- to meter sized drifting animals (zooplankton), plastic particles, detrital aggregates and fecal pellets, fish, whales and many others. These particles and organisms are involved in many different processes and perform a multitude of services, such as in oceanic biogeochemistry (carbon fixation, oxygen production, carbon export and others) or human nourishment (fisheries). Digital optical tools used in pelagic imaging approaches now allow to bridge this enormous size span and to image micro- to meter-sized objects *in situ* or on discrete samples. Monitoring plankton, nekton, and particle dynamics at spatial and temporal scales that enable effective management of marine and freshwater environments poses a collective challenge for society. We here argue that a global, distributed and operational network for pelagic imaging is needed and within reach, and we provide recommendations how it can be attained via the voluntary activities of the pelagic imaging community and strategic support from funding agencies and other stakeholders.

Keywords: Digital imaging, Plankton, Nekton, Detritus, Pelagic ecology

TARGETS OF PELAGIC IMAGING

In principle, all particulate objects floating, sinking or swimming in ponds, rivers, lakes and the ocean, such as detrital particles, planktonic organisms, fish and plastics are targets of pelagic imaging, which makes use of benchtop devices to image discrete samples or underwater camera systems for *in situ* imaging (Figure 1). Whereas *in situ* imaging has the advantage of being non-destructive, discrete samples can be imaged immediately after catch or fixed for later imaging and long-term storage and further subsequent analyses (Lombard et al. 2019, Irisson et al. 2022). Plankton nets are often used to increase the concentration of target objects in discrete samples. The marine snow catcher is a device to obtain intact suspended and sinking particulate matter for imaging and subsequent measurement of further particle characteristics (e.g. respiration rates; (Belcher et al. 2016)), whereas gel traps can be used to collect sinking particulate matter in a suitable fashion for subsequent imaging (Durkin et al. 2021). The capacity to assess plankton, nekton and particles with imaging systems increases the temporal and spatial resolution

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1

attainable when compared to classic studies where humans identify and count the organisms or other targets. Pelagic imaging yields lower taxonomic resolution than such an approach, but can provide other trait information (size distribution, developmental status, symbiotic interactions etc.). The recent and ongoing development of *in situ* imaging technologies that can be deployed at large scales on autonomous platforms, coupled with artificial intelligence and machine learning (AI/ML) for image analysis, promises a solution to overcome the practical limitations of traditional collection and analytical methods (Giering et al. 2022) and opens up new ways for research and ecosystem management. Imaging of individual organisms and particles, as long as the volume analyzed is well quantified, makes it possible to obtain simultaneously: (1) the abundance of different taxonomic groups, their relative contribution to total abundance, biodiversity estimates, as well as the assessment of plastic pollution, (2) morphological or optical characteristics of the organisms and particles that can be used to obtain their biovolume as a proxy of their biomass, to derive size spectra of the imaged objects and other functional traits, (3) contextual information on individual behavior or life cycle traits that can be used to analyze ecological processes (e.g., number of eggs carried to yield information on reproduction capacity, parasitism, predation), and (4) production of a digital archive of images and optical properties that can be shared or reprocessed if more information is needed (Fig. 1). Different imaging systems such as the Cytobuoy (Dubelaar & Gerritzen 2000), IFCB (Olson & Sosik 2007), Planktoscope (Pollina et al. 2022), FlowCam (Poulton 2016), CPICS (Tanaka et al. 2021), Plankton Imager (Pitois et al. 2021), ZooScan (Gorsky et al. 2010), ZooCAM (Romagnan et al. 2016), LOKI (Schulz et al. 2010), UVP5 (Picheral et al. 2010), UVP6 (Picheral et al. 2022), Video Plankton Recorder (Davis et al. 2005), PlanktonScope (Bi et al. 2022), ISIIS (Cowen & Guigand 2008) and PELAGIOS (Hoving et al. 2019), among others are in use to cover the entire size range from microscopic plankton organisms to large fish or gelatinous animals.

PELAGIC IMAGING FOR RESEARCH AND ECOSYSTEM MANAGEMENT

Laboratory-based and *in situ* imaging instruments now generate image data, and hence information on plankton and particle abundance, diversity and size distribution with an unprecedented sampling frequency, comparable to that achieved with environmental probes. Underwater camera systems can be remotely operated from research vessels, on autonomous floats or connected to mooring arrangements to perform observations at relevant spatial and temporal scales. This has led to a revolution in the way we interpret marine ecological processes because instead of integrating plankton diversity, abundance and biomass across depth layers or long time intervals, as achievable with traditional plankton net sampling, researchers can now “see” the aquatic world with much higher resolution than before.

Practical applications of *in situ* imaging systems to characterize aquatic ecosystems and help understand and mitigate environmental impacts are widespread. For instance, the Imaging FlowCytobot (IFCB) has been operating in the Gulf of Mexico for more than 15 years, capturing high-frequency images (at 20-minute intervals) to generate data on microplankton community composition (Fiorendino et al. 2023). This has provided important early warning information on the advection of toxic microalgal blooms towards aquaculture sites, preventing seafood consumption, and thus public health issues and economic losses. The Underwater Vision Profiler - UVP (Picheral et al. 2010, Picheral et al. 2022) has been applied worldwide for more than a decade (Kiko et al. 2022) to estimate particle vertical flux and its influence on the carbon pump, yielding crucial data on biogeochemical cycles (Clements et al. 2022, Clements et al. 2023), revealing un-expected abundance of fragile rhizarians (Biard et al. 2016) and allowing the estimation of the global macro-zooplankton biomass (Drago et al. 2022). Potential impacts of global climate change on marine ecosystems has been investigated using the Zooscan system combined with more traditional methods (Beaugrand et al. 2019). In the offshore fisheries industry,

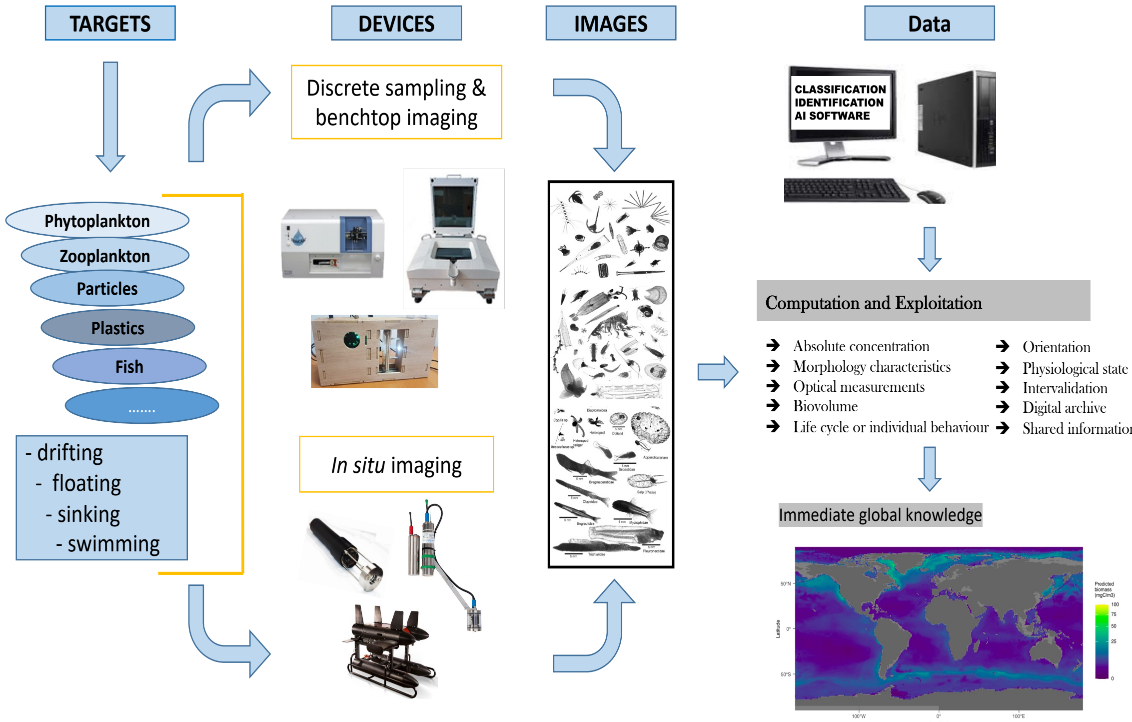

Figure 1. Examples of pelagic imaging workflows

pelagic imaging has been used to perform fish counts and species identification during net trawls, enabling the acquisition of distribution data at fine scales for better interpretation of acoustic results (Allken et al. 2021). Salmon aquaculture facilities in Chile apply regular monitoring of algal blooms and potential pests using the benchtop FlowCAM, an imaging flow cytometer and microscope (Mardones et al. 2022). In addition, imaging acquisition tasks can now be carried out with low-cost instruments such as the recently developed Planktoscope (Pollina et al. 2022), which, as the FlowCam, is a benchtop flow-through imaging system. Combined with other contemporary methods or sensors in aquatic research, such as genomics (Guidi et al. 2016), marine optics (Stemmann et al. 2012) and acoustics (Benoit-Bird & Lawson 2016), pelagic imaging will certainly continue to deliver important insights on the status and development of aquatic environments for decades to come.

However, the new avenue of research opened by pelagic imaging still needs to reach a wider community of scientists, stakeholders and decision-makers. The global south is particularly underrepresented in the pelagic imaging community, a problem demanding efforts in capacity building and technological advances towards more affordable instrumentation. In another perspective, public and private companies are required to carry out environmental impact assessments for licensing purposes in many countries, but pelagic imaging is not included in the methodological provisions to be strictly followed in accordance to the environmental law. For instance, when species-specific biodiversity indices are required, traditional microscopic techniques are the only option to analyze samples to date and thus monitoring is circumscribed to plankton net tows at very low temporal and spatial resolution. However, suitability of pelagic imaging for environmental assessments, albeit not at species level, but at much higher spatial and temporal resolution and with reduced time lag between sampling and data availability, has been demonstrated in open and coastal oceans (Romagnan et al. 2016, Pitois et al. 2021). With the recent development of instruments, data handling software and recognition algorithms (Irisson et al. 2022), some key locks for widespread application of pelagic imaging have been technically resolved. Pelagic imaging - possibly combined with genetic approaches - can lower the costs and increase the resolution for environmental monitoring as a high degree of automation can now be attained.

Despite their numerous advantages, plankton imaging systems have their own limitations. For instance, digital images, especially those captured in-situ, may not always offer high taxonomic resolution, particularly when imaging systems tackle non-constrained, undisturbed water volumes. There exists a trade-off between sampled volume and image quality, which obviously affects the total volume that can be inspected when targeting small-sized organisms or particles, to give an example (Lombard et al. 2019). Similar to traditional plankton net sampling, covering the entire pelagic size spectrum may require the use of multiple imaging systems due to this volume/resolution hurdle. Furthermore, the effectiveness of imaging systems in turbid environments varies depending on the specific imaging technique being employed. Sampling and analytical trade-offs are intrinsic to every sampling method that can be considered in a research program, and should not represent a reason for not adopting pelagic imaging approaches. Other issues that might hinder wider adoption of pelagic imaging such as the often high costs of imaging systems, their often large size - which limits their use on small boats and other flexible vectors - and the complexity of downstream data processing tasks are expected to improve due to ongoing hard- and software development, including open-source initiatives.

Several scientific communities spread in different continents have initiated regional, disciplinary (phytoplankton, or zooplankton) or instrument specific networks that are already used in monitoring programs (Campbell et al. 2013, Benedetti et al. 2019). Few international coordination attempts have been made in the past, for example through the establishment of SCOR working groups (Culverhouse et al. 2014), with the development of open-access internet image repositories (ecotaxa.obs-vlfr.fr) and datasets (Kiko et al. 2022), the organization of international training opportunities (e.g., https://triatlas.w.uib.no/canems/; https://lov.imev-mer.fr/web/facilities/piqv/) or databases combining different instruments (https://www.st.nmfs.noaa.gov/copepod/pssdb/).

However, the user communities of the different imaging devices (e.g. IFCB, UVP, Flowcam, PlanktoScope, Zooscan) are often not formally organized and in particular they are not interconnected (Stemmann & Boss 2012, Ratnarajah et al. 2023). Hence, these spread networking efforts will obviously benefit from further communication that would make protocols, instrument descriptions, QC procedures, data analysis repositories and databases interoperable and accessible for all users (Schoening et al. 2022). However, the concept of a distributed and operational pelagic imaging network goes beyond such simple communication.

CHARACTERISTICS OF A DISTRIBUTED AND OPERATIONAL PELAGIC IMAGING NETWORK

The goal of a distributed network is the sharing of resources, to accomplish a common objective (Srinivasa & Muppalla 2015). In a strict sense, “distributed network” is a term from computer science that describes a network of interconnected computer networks, which are orchestrated to deliver a final data product or service. For our purposes, we can extend this concept to also include digital pelagic imaging devices. Operational oceanography aims to provide routine oceanographic information needed for decision-making purposes and depends on sustained research and development. A multi-platform observation network, a data management system, a data assimilative prediction system, and a dissemination/accessibility system are the core components of operational oceanographic systems (Davidson et al. 2019). The time lag between data acquisition and product provisioning needs to be short enough to enable decision making at the necessary time scale. Hence, for pelagic imaging approaches this needs to be on the order of hours to weeks, if we aim to catch and react to the high frequency and short time events occurring in the ocean (frontal dynamics of eddies, harmful algal blooms, processes related to tidal dynamics). Currently, such a time lag is reached in only a few cases (for example UVP6 on Argo floats (Picheral et al. 2022), phytoplankton monitoring using the Imaging Flow Cytobot (Campbell et al. 2013), real time assessment of *Trichodesmium* blooms with the Video Plankton Recorder (Olson et al. 2015), plankton and micronekton sampling with the ISIIS (Schmid et al. 2023)). In most other cases, it currently takes several months to years for the data obtained with an imaging device to become publicly available, and such data might not be converted into indicators suitable for decision making. Further development of the entire pipeline from image to open access data and the automation of data aggregation and modeling tools will enable us in the near future to deliver products for decision makers that are based on several different, distributed imaging techniques (e.g. covering different size-ranges and stemming from different research groups), possibly even integrated with other environmental sensor data. Once the framework is established, users (scientists and monitoring agencies) can select an imaging strategy adapted to their specific, possibly local context, but can also automatically contribute with their datasets to a wider context and thereby benefit research and society in several ways. As a first example, mesoscale plankton dynamics can be studied using a UVP6-LP mounted on a BGC Argo float (Picheral et al. 2022). As the data is collected and made available via an open access server system, it can also be included in global datasets and hence benefit the global carbon cycle assessment. Further developing and interfacing the different spread pelagic imaging networks with this first prototype of an operational pelagic imaging platform could lead to the envisioned distributed and operational pelagic imaging network.

HOW CAN WE REALIZE A DISTRIBUTED AND OPERATIONAL PELAGIC IMAGING NETWORK IN THE NEAR FUTURE?

To reach the goal of a Distributed and Operational Pelagic Imaging Network, we first of all need the pelagic imaging research community to embrace this concept and to commit to the open science approach of operational oceanography. In particular, raw data needs to be released directly after recovery while quality control and target identification should be conducted in a delayed mode. To enable this, funders need to recognize the extreme value of pelagic imaging approaches and the added value of an operational pelagic imaging network. It will increase the value of funding that goes into individual imaging approaches, as it promotes the connected reuse of data and hence provides higher level products. However, this distributed network requires support for coordination, development, maintenance and infrastructure that funding agencies need to consider.

We recommend the following voluntary activities that will pave the way towards a distributed and operational Pelagic Imaging Network:

- Stakeholder engagement
  - Raise awareness for the importance of plankton for global food security, ocean health and global biogeochemical cycles.
  - Promote discussions at all levels - international, local, high-level, informal - on the current status and future of pelagic imaging in marine and freshwater environments.
  - Train the next generation of scientists, not only in the use of single imaging devices, but also teach how different image datasets can be merged and how artificial intelligence and network tools can be used to process the data.
  - Establish and maintain repositories for best practices guidelines, processing software, benchmark image datasets, research datasets and derived products. A first collection of such tools can be found at

https://www.aa-mari.net/i-itapina-online-resources/.

- Technological developments
  - Further develop imaging instruments and server hardware via the integration of technological improvements in optics and computer systems. Backwards compatibility should be considered during these developments, to e.g. enable the maintenance and consistency of long-term time series.
  - During development, prioritize the establishment of low-cost approaches (such as the PlanktoScope). This will increase applicability in developing countries and for citizen scientists, and will result in widespread adoption of pelagic imaging techniques. The inter- and intra operability of new instruments, their data processing tools and data output should also be considered, to enable imaging hardware agnostic software development.
  - Further develop data pipelines that enable the fast and automated processing and upload of image data to central server systems or archives. These server systems and archives should also enable the automated download of images and/or data by higher level network components.

- Data merging and product development
  - Consider and enable the integration of imaging data with other data sources. In particular environmental data such as temperature, salinity, oxygen concentration and nutrient levels, genetic data and other data types should be archived together, or linked to the image data.
  - Develop pelagic imaging based environmental indicators and products to reduce the costs and increase the spatial and temporal resolution of environmental monitoring approaches.

As there currently is no funding available to enable the coordinated development of a Distributed and Operational Pelagic Imaging Network, all of the above suggestions should be embraced by the pelagic imaging community. The establishment of a scientific association may help achieve these goals within a reasonable time frame and assist with the implementation, maintenance, and expansion of the proposed Distributed and Operational Pelagic Imaging Network. Such an “International Union of Pelagic Imaging – (IUPI)" would have the mission to foster regional and global efforts to generate, integrate and disseminate knowledge on pelagic imaging, connecting scientists and institutions around the world.

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AUTHOR CONTRIBUTIONS

R.K., R.M.L., Y.D.S., L.S. : Conceptualization; Writing – original draft; Writing – review & editing

REFERENCES

ALLKEN, V., ROSEN, S., HANDEGARD, N. O. & MALDE, K. 2021. A deep learning-based method to identify and count pelagic and mesopelagic fishes from trawl camera images, *ICES Journal of Marine Science* 78(10), 3780–3792.

BEAUGRAND, G., CONVERSI, A., ATKINSON, A., CLOERN, J., CHIBA, S., Fonda-Umani, S., KIRBY, R. R., GREENE, C. H., GOBERVILLE, E., OTTO, S. A., REID, P. C., STEMMANN, L. & EDWARDS, M. 2019. Prediction of unprecedented biological shifts in the global ocean, *Nature Climate Change* 9(3), 237–243.

BELCHER, A., IVERSEN, M., GIERING, S., RIOU, V., HENSON, S. A., BERLINE, L., GUILLOUX, L. & SANDERS, R. 2016. Depth-resolved particle-associated microbial respiration in the northeast Atlantic, *Biogeosciences* 13(17), 4927–4943.

BENEDETTI, F., JALABERT, L., SOURISSEAU, M., BECKER, B., CAILLIAU, C., DESNOS, C., ELINEAU, A., IRISSON, J.-O., LOMBARD, F., PICHERAL, M., STEMMANN, L. & POULINE, P. 2019. The Seasonal and Inter-Annual Fluctuations of Plankton Abundance and Community Structure in a North Atlantic Marine Protected Area, *Frontiers in Marine Science* 6.

Benoit-Bird, K. J. & LAWSON, G. L. 2016. Ecological Insights from Pelagic Habitats Acquired Using Active Acoustic Techniques, *Annual Review of Marine Science* 8(1), 463–490.

BI, H., SONG, J., ZHAO, J., LIU, H., CHENG, X., WANG, L., CAI, Z., BENFIELD, M. C., OTTO, S., GOBERVILLE, E., KEISTER, J., YANG, Y., YU, X., CAI, J., YING, K. & CONVERSI, A. 2022. Temporal characteristics of plankton indicators in coastal waters: High-frequency data from PlanktonScope, *Journal of Sea Research* 189, 102283.

BIARD, T., STEMMANN, L., PICHERAL, M., MAYOT, N., VANDROMME, P., HAUSS, H., GORSKY, G., GUIDI, L., KIKO, R. & NOT, F. 2016. In situ imaging reveals the biomass of giant protists in the global ocean, *Nature* 532(7600), 504–507.

CAMPBELL, L., HENRICHS, D. W., OLSON, R. J. & SOSIK, H. M. 2013. Continuous automated imaging-in-flow cytometry for detection and early warning of *Karenia brevis* blooms in the Gulf of Mexico, *Environmental Science and Pollution Research* 20(10), 6896–6902.

CLEMENTS, D. J., YANG, S., WEBER, T., MCDONNELL, A. M. P., KIKO, R., STEMMANN, L. & BIANCHI, D. 2022. Constraining the Particle Size Distribution of Large Marine Particles in the Global Ocean With In Situ Optical Observations and Supervised Learning, *Global Biogeochemical Cycles* 36(5), e2021GB007276.

CLEMENTS, D. J., YANG, S., WEBER, T., MCDONNELL, A. M. P., KIKO, R., STEMMANN, L. & BIANCHI, D. 2023. New Estimate of Organic Carbon Export From Optical Measurements Reveals the Role of Particle Size Distribution and Export Horizon, *Global Biogeochemical Cycles* 37(3), e2022GB007633.

COWEN, R. K. & GUIGAND, C. M. 2008. In situ ichthyoplankton imaging system (ISIIS): System design and preliminary results, *Limnology and Oceanography: Methods* 6(2), 126–132.

CULVERHOUSE, P. F., MACLEOD, N., WILLIAMS, R., BENFIELD, M. C., LOPES, R. M. & PICHERAL, M. 2014. An empirical assessment of the consistency of taxonomic identifications, *Marine Biology Research* 10(1), 73–84.

DAVIDSON, F., Alvera-Azcárate, A., BARTH, A., BRASSINGTON, G. B., CHASSIGNET, E. P., CLEMENTI, E., De Mey-Frémaux, P., DIVAKARAN, P., HARRIS, C., HERNANDEZ, F., HOGAN, P., HOLE, L. R., HOLT, J., LIU, G., LU, Y., LORENTE, P., MAKSYMCZUK, J., MARTIN, M., MEHRA, A., MELSOM, A.,

MO, H., MOORE, A., ODDO, P., PASCUAL, A., PEQUIGNET, A.-C., KOURAFALOU, V., RYAN, A., SIDDORN, J., SMITH, G., SPINDLER, D., SPINDLER, T., STANEV, E. V., STANEVA, J., STORTO, A., TANAJURA, C., VINAYACHANDRAN, P. N., WAN, L., WANG, H., ZHANG, Y., ZHU, X. & ZU, Z. 2019. Synergies in Operational Oceanography: The Intrinsic Need for Sustained Ocean Observations, *Frontiers in Marine Science* 6.

DAVIS, C. S., THWAITES, F. T., GALLAGER, S. M. & HU, Q. 2005. A three-axis fast-tow digital Video Plankton Recorder for rapid surveys of plankton taxa and hydrography, *Limnology and Oceanography: Methods* 3(2), 59–74.

DRAGO, L., PANAÏOTIS, T., IRISSON, J.-O., BABIN, M., BIARD, T., CARLOTTI, F., COPPOLA, L., GUIDI, L., HAUSS, H., Karp-Boss, L., LOMBARD, F., MCDONNELL, A. M. P., PICHERAL, M., ROGGE, A., WAITE, A. M., STEMMANN, L. & KIKO, R. 2022. Global Distribution of Zooplankton Biomass Estimated by In Situ Imaging and Machine Learning, *Frontiers in Marine Science* 9.

DUBELAAR, G. B. J. & GERRITZEN, P. L. 2000. CytoBuoy: A step forward towards using flow cytometry in operational oceanography, *Scientia Marina* 64(2), 255–265.

DURKIN, C. A., BUESSELER, K. O., CETINIĆ, I., ESTAPA, M. L., KELLY, R. P. & OMAND, M. 2021. A Visual Tour of Carbon Export by Sinking Particles, *Global Biogeochemical Cycles* 35(10), e2021GB006985.

FIORENDINO, J. M., GAONKAR, C. C., HENRICHS, D. W. & CAMPBELL, L. 2023. Drivers of microplankton community assemblage following tropical cyclones, *Journal of Plankton Research* 45(1), 205–220.

GIERING, S. L. C., CULVERHOUSE, P. F., JOHNS, D. G., McQuatters-Gollop, A. & PITOIS, S. G. 2022. Are plankton nets a thing of the past? An assessment of in situ imaging of zooplankton for large-scale ecosystem assessment and policy decision-making, *Frontiers in Marine Science* 9.

GORSKY, G., OHMAN, M. D., PICHERAL, M., GASPARINI, S., STEMMANN, L., ROMAGNAN, J.-B., CAWOOD, A., PESANT, S., García-Comas, C. & PREJGER, F. 2010. Digital zooplankton image analysis using the ZooScan integrated system, *Journal of Plankton Research* 32(3), 285–303.

GUIDI, L., CHAFFRON, S., BITTNER, L., EVEILLARD, D., LARHLIMI, A., ROUX, S., DARZI, Y., AUDIC, S., BERLINE, L., BRUM, J. R., COELHO, L. P., ESPINOZA, J. C. I., MALVIYA, S., SUNAGAWA, S., DIMIER, C., Kandels-Lewis, S., PICHERAL, M., POULAIN, J., SEARSON, S., STEMMANN, L., NOT, F., HINGAMP, P., SPEICH, S., FOLLOWS, M., Karp-Boss, L., BOSS, E., OGATA, H., PESANT, S., WEISSENBACH, J., WINCKER, P., ACINAS, S. G., BORK, P., de Vargas, C., IUDICONE, D., SULLIVAN, M. B., RAES, J., KARSENTI, E., BOWLER, C. & GORSKY, G. 2016. Plankton networks driving carbon export in the oligotrophic ocean, *Nature* 532(7600), 465–470.

HOVING, H.-J., CHRISTIANSEN, S., FABRIZIUS, E., HAUSS, H., KIKO, R., LINKE, P., NEITZEL, P., PIATKOWSKI, U. & KÖRTZINGER, A. 2019. The Pelagic In situ Observation System (PELAGIOS) to reveal biodiversity, behavior, and ecology of elusive oceanic fauna, *Ocean Science* 15(5), 1327–1340.

IRISSON, J.-O., AYATA, S.-D., LINDSAY, D. J., Karp-Boss, L. & STEMMANN, L. 2022. Machine Learning for the Study of Plankton and Marine Snow from Images, *Annual Review of Marine Science* 14(1), annurev–marine–041921–013023.

KIKO, R., PICHERAL, M., ANTOINE, D., BABIN, M., BERLINE, L., BIARD, T., BOSS, E., BRANDT, P., CARLOTTI, F., CHRISTIANSEN, S., COPPOLA, L., de la Cruz, L., Diamond-Riquier, E., Durrieu de Madron, X., ELINEAU, A., GORSKY, G., GUIDI, L., HAUSS, H., IRISSON, J.-O., Karp-Boss, L., KARSTENSEN, J., KIM, D.-G., LEKANOFF, R. M., LOMBARD, F., LOPES, R. M., MAREC,

C., MCDONNELL, A. M. P., NIEMEYER, D., NOYON, M., O'DALY, S. H., OHMAN, M. D., PRETTY, J. L., ROGGE, A., SEARSON, S., SHIBATA, M., TANAKA, Y., TANHUA, T., TAUCHER, J., TRUDNOWSKA, E., TURNER, J. S., WAITE, A. & STEMMANN, L. 2022. A global marine particle size distribution dataset obtained with the Underwater Vision Profiler 5, *Earth System Science Data* 14(9), 4315–4337.

LOMBARD, F., BOSS, E., WAITE, A. M., VOGT, M., UITZ, J., STEMMANN, L., SOSIK, H. M., SCHULZ, J., ROMAGNAN, J.-B., PICHERAL, M., PEARLMAN, J., OHMAN, M. D., NIEHOFF, B., MÖLLER, K. O., MILOSLAVICH, P., Lara-Lpez, A., KUDELA, R., LOPES, R. M., KIKO, R., Karp-Boss, L., JAFFE, J. S., IVERSEN, M. H., IRISSON, J.-O., FENNEL, K., HAUSS, H., GUIDI, L., GORSKY, G., GIERING, S. L. C., GAUBE, P., GALLAGER, S., DUBELAAR, G., COWEN, R. K., CARLOTTI, F., Briseño-Avena, C., BERLINE, L., Benoit-Bird, K., BAX, N., BATTEN, S., AYATA, S. D., ARTIGAS, L. F. & APPELTANS, W. 2019. Globally Consistent Quantitative Observations of Planktonic Ecosystems, *Frontiers in Marine Science* 6.

MARDONES, J. I., KROCK, B., MARCUS, L., Alves-de-Souza, C., NAGAI, S., YARIMIZU, K., CLÉMENT, A., CORREA, N., SILVA, S., Paredes-Mella, J. & VON DASSOW, P. 2022. Chapter 4 - From molecules to ecosystem functioning: Insight into new approaches to taxonomy to monitor harmful algae diversity in Chile, *in* L. A. Clementson, R. S. Eriksen & A. Willis (eds), *Advances in Phytoplankton Ecology*, Elsevier, 119–154.

OLSON, E. M., MCGILLICUDDY, D. J., FLIERL, G. R., DAVIS, C. S., DYHRMAN, S. T. & WATERBURY, J. B. 2015. Mesoscale eddies and *Tichodesmium* spp. distributions in the southwestern North Atlantic, *Journal of Geophysical Research: Oceans* 120(6), 4129–4150.

OLSON, R. J. & SOSIK, H. M. 2007. A submersible imaging-in-flow instrument to analyze nano-and microplankton: Imaging FlowCytobot, *Limnology and Oceanography: Methods* 5(6), 195–203.

PICHERAL, M., CATALANO, C., BROUSSEAU, D., CLAUSTRE, H., COPPOLA, L., LEYMARIE, E., COINDAT, J., DIAS, F., FEVRE, S., GUIDI, L., IRISSON, J. O., LEGENDRE, L., LOMBARD, F., MORTIER, L., PENKERCH, C., ROGGE, A., SCHMECHTIG, C., THIBAULT, S., TIXIER, T., WAITE, A. & STEMMANN, L. 2022. The Underwater Vision Profiler 6: An imaging sensor of particle size spectra and plankton, for autonomous and cabled platforms, *Limnology and Oceanography: Methods* 20(2), 115–129.

PICHERAL, M., GUIDI, L., STEMMANN, L., KARL, D. M., IDDAOUD, G. & GORSKY, G. 2010. The Underwater Vision Profiler 5: An advanced instrument for high spatial resolution studies of particle size spectra and zooplankton, *Limnology and Oceanography: Methods* 8(9), 462–473.

PITOIS, S. G., GRAVES, C. A., CLOSE, H., LYNAM, C., SCOTT, J., TILBURY, J., van der Kooij, J. & CULVERHOUSE, P. 2021. A first approach to build and test the Copepod Mean Size and Total Abundance (CMSTA) ecological indicator using in-situ size measurements from the Plankton Imager (PI), *Ecological Indicators* 123, 107307.

POLLINA, T., LARSON, A. G., LOMBARD, F., LI, H., LE GUEN, D., COLIN, S., de Vargas, C. & PRAKASH, M. 2022. PlanktoScope: Affordable Modular Quantitative Imaging Platform for Citizen Oceanography, *Frontiers in Marine Science* 9.

POULTON, N. J. 2016. FlowCam: Quantification and Classification of Phytoplankton by Imaging Flow Cytometry, *in* N. S. Barteneva & I. A. Vorobjev (eds), *Imaging Flow Cytometry: Methods and Protocols*, Methods in Molecular Biology, Springer, New York, NY, 237–247.

RATNARAJAH, L., Abu-Alhaija, R., ATKINSON, A., BATTEN, S., BAX, N. J., BERNARD, K. S., CANONICO, G., CORNILS, A., EVERETT, J. D., GRIGORATOU, M., ISHAK, N. H. A.,

JOHNS, D., LOMBARD, F., MUXAGATA, E., OSTLE, C., PITOIS, S., RICHARDSON, A. J., SCHMIDT, K., STEMMANN, L., SWADLING, K. M., YANG, G. & YEBRA, L. 2023. Monitoring and modelling marine zooplankton in a changing climate, *Nature Communications* 14(1), 564.

ROMAGNAN, J. B., ALDAMMAN, L., GASPARINI, S., NIVAL, P., AUBERT, A., JAMET, J. L. & STEMMANN, L. 2016. High frequency mesozooplankton monitoring: Can imaging systems and automated sample analysis help us describe and interpret changes in zooplankton community composition and size structure — An example from a coastal site, *Journal of Marine Systems* 162, 18–28.

SCHMID, M. S., DAPRANO, D., DAMLE, M. M., SULLIVAN, C. M., SPONAUGLE, S., COUSIN, C., GUIGAND, C. & COWEN, R. K. 2023. Edge computing at sea: High-throughput classification of in-situ plankton imagery for adaptive sampling, *Frontiers in Marine Science* 10.

SCHOENING, T., DURDEN, J. M., FABER, C., FELDEN, J., HEGER, K., HOVING, H.-J. T., KIKO, R., KÖSER, K., KRÄMMER, C., KWASNITSCHKA, T., MÖLLER, K. O., NAKATH, D., NASS, A., NATTKEMPER, T. W., PURSER, A. & ZUROWIETZ, M. 2022. Making marine image data FAIR, *Scientific Data* 9(1), 414.

SCHULZ, J., BARZ, K., AYON, P., LÜDTKE, A., ZIELINSKI, O., MENGEDOHT, D. & HIRCHE, H.-J. 2010. Imaging of plankton specimens with the lightframe on-sight keyspecies investigation (LOKI) system, *Journal of the European Optical Society - Rapid publications* 5(0).

SRINIVASA, K. G. & MUPPALLA, A. K. 2015. Introduction, *in* K. Srinivasa & A. K. Muppalla (eds), *Guide to High Performance Distributed Computing: Case Studies with Hadoop, Scalding and Spark*, Computer Communications and Networks, Springer International Publishing, Cham, 3–31.

STEMMANN, L., CLAUSTRE, H. & D'ORTENZIO, F. 2012. Integrated observation system for pelagic ecosystems and biogeochemical cycles in the oceans., *Sensors for ecology: Towards integrated knowledge of ecosystems* 1, 261–278.

STEMMANN, L. & BOSS, E. 2012. Plankton and Particle Size and Packaging: From Determining Optical Properties to Driving the Biological Pump, *Annual Review of Marine Science* 4(1), 263–290.

TANAKA, M., GENIN, A., ENDO, Y., IVEY, G. N. & YAMAZAKI, H. 2021. The potential role of turbulence in modulating the migration of demersal zooplankton, *Limnology and Oceanography* 66(3), 855–864.