INNOVATIVE TECHNOLOGY IN **BLUE NATURAL CAPITAL PROJECTS**

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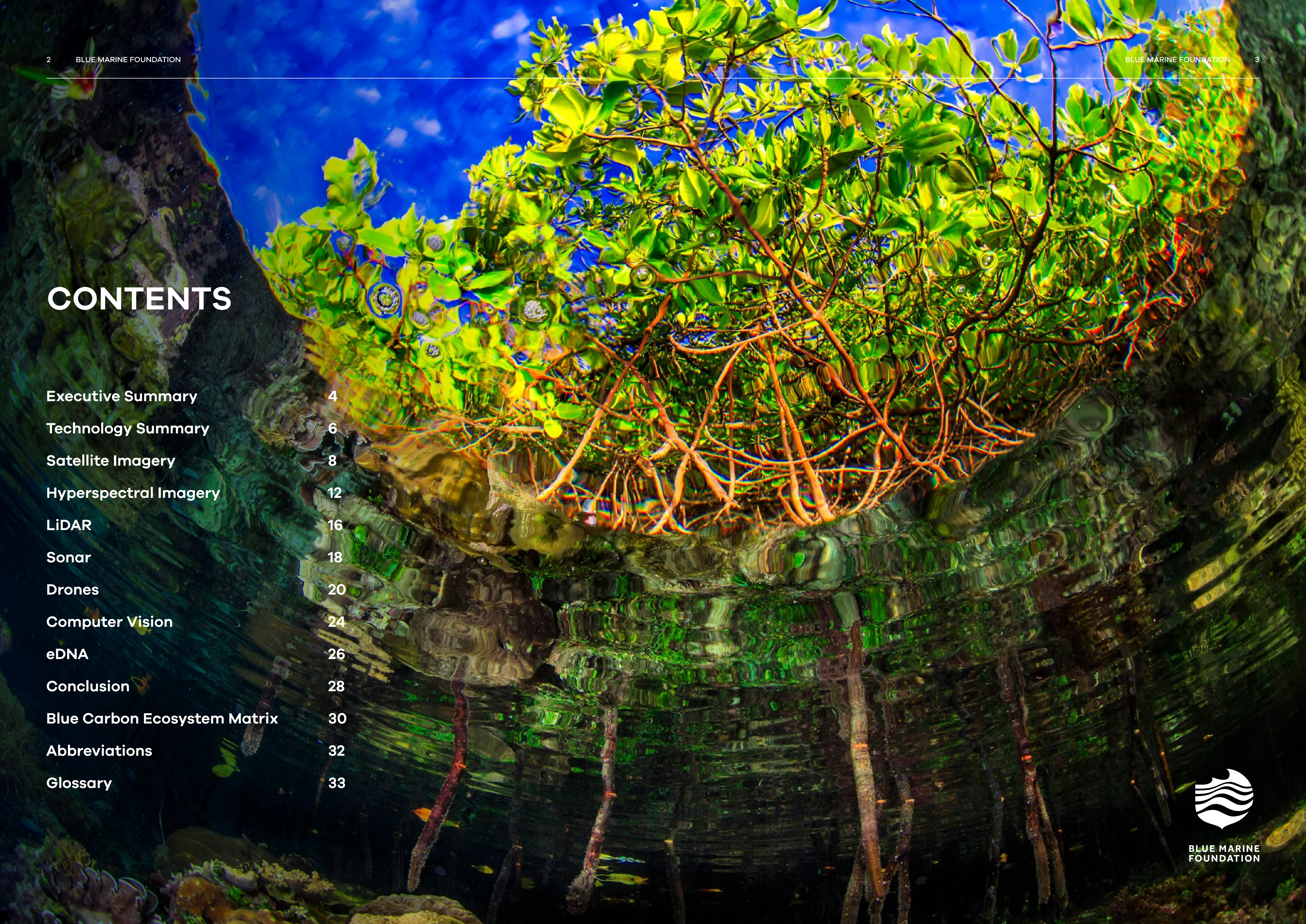
BLUE MARINE FOUNDATION

Photo: Mike Guest



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EXECUTIVE SUMMARY

The ocean and its natural capital is under threat from multiple human pressures, from climate change to overfishing. There is no single solution, but technologies suitable for use within blue natural capital projects are emerging rapidly, as young entrepreneurs and investment crowds into the space.

This report looks at a number of different technological solutions, outlining both the current state and the future potential for the mapping, monitoring, protection and restoration of blue natural capital. This technology already includes satellites and sonar, drones and computer vision, hyperspectral cameras and environmental DNA. Our vision is for a future when the values provided by the marine environment are quantified and rewarded, where creatures like the native oyster are rightfully acknowledged as very valuable for the services they provide. In this future local communities could deploy inexpensive, out-of-the-box technology to play an active role in monitoring the values provided by their blue natural capital assets.

Above all else, technology could ensure that blue carbon and other blue natural capital projects support a healthy, abundant marine environment.

If done in the right way, technology could enable a new level of investment in marine conservation and restoration projects.

Just like restoration of marine habitats is moving to a more sophisticated seascape approach, so too new combinations of technology could enhance our understanding of the marine environment.

Dan Crockett,
Director of Ocean and Climate,
Blue Marine Foundation

Key findings of the report are:

1. There is always a compromise between data quality and geographic coverage, with different technologies appropriate for different use cases. For example, to map small-scale blue carbon ecosystems (BCE), precise technology such as drones can be used, but for country-wide mapping of ecosystems, medium resolution satellite data is the only viable option.

2. While technology is progressing to make measurement, reporting and verification (MRV) of BCE more scalable, verification bodies continue to require ground truthing. Ground truthing is time and cost consumptive, so hinders the scalability and democratisation of blue carbon projects. This will be overcome with continued improvements in technology, quality of and trust in the data provided, and the active involvement of respected carbon standard bodies such as Plan Vivo.

3. Despite progress in available technology, the highest quality technologies (e.g., hyperspectral imagery or LiDAR) are not accessible to local communities. The tools that are accessible, such as The Google Earth Engine Mangrove Mapping Methodology (GEEMMM), allow for basic ecosystem management rather than precise data for carbon or biodiversity verification. Lessons can be learnt from land-based initiatives such as Drones for Justice[1], educating and co-owning drones with low-income local stakeholders.

[1] Radjawali, I. and Pye, O. (2017). Drones for justice: inclusive technology and river-related action research along the Kapuas. Geographica Helvetica, 72(1), pp.17–27. doi:https://doi.org/10.5194/gh-72-17-2017.

TECHNOLOGY SUMMARY

SATELLITE IMAGERY

refers to images of earth collected by satellite. Satellite imagery allows for scalable and precise ecosystem mapping, particularly for mangroves. In the future, cloud computing and visualisation platforms will need to bear the load of high quality data for it to be accessible to non-experts and local stakeholders.

LIDAR

is a method of mapping the seabed using a pulsed laser to measure distances and create accurate 3D maps of the ocean floor. Mapping ecosystem topography and vegetation height, LiDAR data is particularly valuable since vegetation architecture, including plant height and biomass, are important data points in the estimation of carbon stocks.

HYPERSPECTRAL IMAGERY

captures many spectral bands, including beyond what is visible to the human eye. Hyperspectral imagery is particularly effective at identifying vegetation species and health, useful in accurate ecosystem mapping and monitoring. The technology's scalability and accessibility is currently limited by the cost and inefficiency of data collection and analysis.

SONAR MAPPING

is a technique to map the seafloor and sub-seafloor with sound waves. Echosounders' beams are able to infiltrate metres below the seabed, providing valuable information on soil qualities including carbon value, as well as seabed topography and vegetation cover. While this technology is in its infancy, it has potential in the scalable estimation of seabed and ecosystem sediment soil carbon stocks.

DRONES

are machines that fly without a pilot carrying sensors, often visual, thermal or hyperspectral imagery. Drones are easily deployable, high resolution and affordable for high income stakeholders. Cost and technical limitations still limit access to low-income local stakeholders, where technical and financial innovation is needed.

eDNA

is DNA released from organisms into the environment, which is analysed and used for evidence-based biodiversity monitoring. Data is collected on species presence, biodiversity estimates, as well as further information about ecosystem dynamics.

COMPUTER VISION

is a field of AI in which computer systems derive information from images and videos. Computer vision has the potential to revolutionise ecosystem and animal monitoring by not only bearing the burden of the vast amounts of collected data but also transforming the quality of insights taken from this data.

SATELLITE IMAGERY

TECHNOLOGY

Satellites are simply machines that orbit the earth carrying sensors[2]. Since they vary in sensor suite (sensors carried), spatial resolution (size of one pixel) and temporal resolution (time between measurements), there's no one-size-fits-all technology. Satellites can support optical (for visual and hyperspectral imagery), infrared, synthetic aperture radar (SAR) and light detection and ranging (LiDAR) sensors, to name a few. In spatial resolution, satellites vary from medium resolution Landsat (30m resolution) to high resolution satellites such as WorldView-3 (31cm resolution). In temporal resolution, while Landsat has provided data every two weeks since 1972, Planet Labs (50cm resolution) provides 2 to 12 images of a given location per day.

USES

The most common use for satellite imagery in blue natural capital is the mapping and monitoring of ecosystems, as seen with mangroves (e.g., GEEMMM[3]), kelp (e.g., Kelpwatch[4]) and coral reefs (e.g., The Allen Coral Atlas[5]). The foundation of ecosystem mapping is visual satellite imagery, using light visible to the human eye similar to aerial photography. Additionally, other sensor data can aid ecosystem mapping, for example with hyperspectral data allowing for precise species identification. Ecosystem identification post-data collection is increasingly done using AI for efficiency and precision[6].

Regarding the mapping of BCE, different satellite technology is required for different project sizes. For large-scale (>1000 hectares) mapping, for example to inform nationally determined contributions (NDCs), medium-resolution satellites (e.g., Landsat, 30m resolution) are suitable, but for small (<100 hectares) and medium-scale (<1000 hectares) individual projects, higher-resolution satellites (<2m to 10m resolution) are required[7]. The reasons for this are; (i) individual projects require more precision than NDCs to verify carbon data; (ii) unlike individual projects, NDCs require baseline data to 1990[8], limiting to a handful of available satellites including Landsat; (iii) the size of individual projects makes high resolution data analytically necessary, despite the fact this may be financially challenging, particularly for local stakeholders from low-income countries.

Satellite imagery is also used in the mapping and monitoring of biodiversity through marine animal tracking. For decades, wildlife and biodiversity were monitored using habitable land as a proxy, but with the availability of high-resolution satellites (<1m resolution), this has evolved to include the detection of individual animals such as polar bears, seals and albatross[9]. Difficulty is encountered for subsurface animals, though larger subsurface animals that come to the surface, such as whales, can be monitored (e.g., Spacewhale)[10].

Illegal, unreported and unregulated (IUU) fishing in marine protected areas (MPAs) is also monitored by satellite imagery, as medium resolution satellite data (e.g., Sentinel-2, 10m), allows for the identification of fishing vessels upwards of ~10m. Platforms such as Ocean Mind[11] and Global Fishing Watch Marine Manager[12] make this actionable and accessible by combining satellite data with other data sources including port and GPS data.

The most common use for satellite imagery in blue natural capital is the mapping and monitoring of ecosystems, as seen with mangroves, kelp and coral reefs.

CHALLENGES

Optical sensors face particular challenges due to their reliance on light. Optical sensors have difficulty monitoring subsurface activity due to breaking waves, water clarity and sun glint, with clouds often preventing imagery altogether. They achieve high accuracy in mangrove forest mapping but are less effective with seagrass, kelp and coral reefs. However, there have been promising anomalies, such as researchers from the German Aerospace Centre reaching 90% accuracy using satellite imagery to map seagrass in the Aegean Sea[13]. Such impressive results can be explained by sympathetic conditions, such as the seagrass' dense nature and clear shallow waters[7].

Optical sensors are also limited to mapping vegetation cover rather than providing information about habitat architecture, particularly vegetation height, which is important for mangrove and tidal marsh health and carbon value[14]. While satellites such as Planet have shown promise in estimating tree height, this is not at the precision required for tidal marsh vegetation change. However, carbon intelligence platform Sylvera have developed technology to collect data on vegetation canopy height, cover and biomass using multiple satellite sensors, including LiDAR, SAR and optical imagery[15].

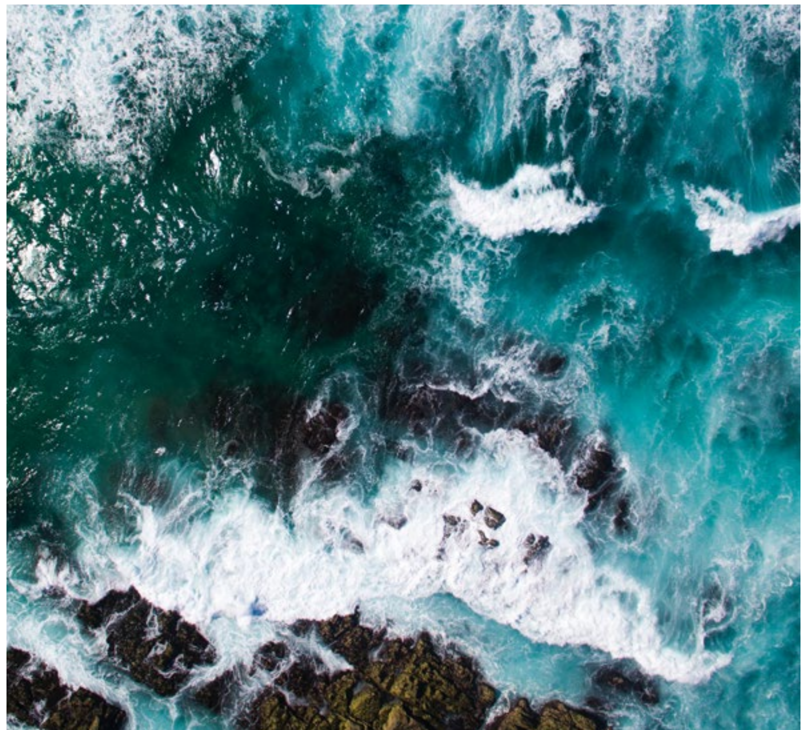
Machine learning is used to estimate carbon stocks and inform their credit rating. Showing promise for mangroves, Sylvera's technology has primarily been used for land-based projects.

While medium resolution imagery (e.g., Landsat, 30m) is free to access, high resolution imagery comes at a cost. For example, WorldView-3 (31cm) costs ~US$250 per 10km^2, a price that compounds for temporal resolution[16]. Recent initiatives to democratise access to satellite imagery have shown promise, such as the Norwegian Government's partnership with Planet, making their high spatial (5m) and temporal (2-12 images a day) images of tropical forests freely available[17].

Building on this, a growing number of software tools are making satellite data more accessible. A core component of this is computing power and data analysis, made freely available through Google Earth Engine (GEE), with data visualisation platforms allowing for non-expert use. A good example of this is the Allen Coral Atlas, a freely available platform that uses GEE and AI to map global coral reefs and monitor coral bleaching.

FUTURE

The future role of satellite technology is in the scalability of precise ecosystem mapping and monitoring, particularly mangroves and to a lesser extent subsurface ecosystems. Spatial and temporal resolution is increasing, AI is improving mapping accuracy and multi-sensor approaches are increasing precision. Cloud computing and visualisation platforms will need to bear the load of this increasingly high quality data for it to be accessible to non-experts and local stakeholders.



CASE STUDY:
GEEMMM (BLUE VENTURES)[18]

The GEEMMM is a free platform allowing local non-expert managers to map and monitor mangroves. Developed by Blue Ventures, the GEEMMM is an open-source tool, run on the GEE platform (15m resolution). With users from researchers to local conservation organisations, the platform suits small-scale projects, informing further research rather than replacing it. The GEEMMM only requires computer access (with mobile capability coming soon) and simple online training.

[2] May, S. (2014). What Is a Satellite? [online] NASA. Available at: https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-a-satellite-58.html.

[3] Blue Ventures. (n.d.). The Google Earth Engine Mangrove Mapping Methodology (GEEMMM). [online] Available at: https://blueventures.org/publications/the-google-earth-engine-mangrove-mapping-methodology-geemmm/ [Accessed 24 April 2023].

[4] kelpwatch.org. (n.d.). Kelpwatch.org. [online] Available at: https://kelpwatch.org/.

[5] allencoralatlas.org. (n.d.). Allen Coral Atlas. [online] Available at: https://allencoralatlas.org/.

[6] allencoralatlas.org. (n.d.). Rapid repeat monitoring of reef threats | Allen Coral Atlas Blog. [online] Available at: https://www.allencoralatlas.org/blog/rapid-repeat-monitoring-of-reef-threats/ [Accessed 01 May 2023].

[7] Malerba, M.E., Duarte de Paula Costa, M., Friess, D.A., Schuster, L., Young, M.A., Lagomasino, D., Serrano, O., Hickey, S.M., York, P.H., Rasheed, M., Lefcheck, J.S., Radford, B., Atwood, T.B., Ierodiaconou, D. and Macreadie, P. (2023). Remote sensing for cost-effective blue carbon accounting. Earth-Science Reviews, [online] 238, p.104337. doi:https://doi.org/10.1016/j.earscirev.2023.104337.

[8] UNFCCC (2015). The Paris Agreement. [online] UNFCCC. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement.

[9] Höschle, C., Cubaynes, H.C., Clarke, P.J., Humphries, G. and Borowicz, A. (2021). The Potential of Satellite Imagery for Surveying Whales. Sensors, 21(3), p.963. doi:https://doi.org/10.3390/s21030963.

[10] Spacewhales. (n.d.). AI Detected Whales. [online] Available at: https://www.spacewhales.de/ [Accessed 18 April 2023].

[11] Oceanmind. (n.d.). OceanMind. [online] Available at: https://oceanmind.global/ [Accessed 03 May 2023].

[12] Global Fishing Watch. (n.d.). Marine Manager - Management Technology. [online] Available at: https://globalfishingwatch.org/marine-manager-portal/ [Accessed 18 April 2023].

[13] Traganos, D., Aggarwal, B., Poursanidis, D., Topouzelis, K., Chrysoulakis, N. and Reinartz, P. (2018). Towards Global-Scale Seagrass Mapping and Monitoring Using Sentinel-2 on Google Earth Engine: The Case Study of the Aegean and Ionian Seas. Remote Sensing, 10(8), p.1227. doi:https://doi.org/10.3390/rs10081227.

[14] Asner, G.P., Mascaro, J., Muller-Landau, H.C., Vieilledent, G., Vaudry, R., Rasamoelina, M., Hall, J.S. and van Breugel, M. (2012). A universal airborne LiDAR approach for tropical forest carbon mapping. Oecologia, [online] 168(4), pp.1147–1160. Available at: https://www.jstor.org/stable/41487351.

[15] www.sylvera.com. (n.d.). How Sylvera uses machine learning to assess carbon projects. [online] Available at: https://www.sylvera.com/blog/how-sylvera-uses-machine-learning [Accessed 23 May. 2023].

[16] Malerba, M.E., Duarte de Paula Costa, M., Friess, D.A., Schuster, L., Young, M.A., Lagomasino, D., Serrano, O., Hickey, S.M., York, P.H., Rasheed, M., Lefcheck, J.S., Radford, B., Atwood, T.B., Ierodiaconou, D. and Macreadie, P. (2023). Remote sensing for cost-effective blue carbon accounting. Earth-Science Reviews, [online] 238, p.104337. doi:https://doi.org/10.1016/j.earscirev.2023.104337.

[17] Global Forest Watch Content. (2020). High-Resolution Imagery Now Free on GFW | Global Forest Watch Blog. [online] Available at: https://www.globalforestwatch.org/blog/data-and-research/planet-high-resolution-imagery/ [Accessed 03 May 2023].

[18] Blue Ventures. (n.d.). The Google Earth Engine Mangrove Mapping Methodology (GEEMMM). [online] Available at: https://blueventures.org/publications/the-google-earth-engine-mangrove-mapping-methodology-geemmm.

HYPERSPECTRAL IMAGERY

TECHNOLOGY

Hyperspectral imagery refers to imaging using many (>100) spectral bands[19], capturing information beyond what is visible to the human eye. Hyperspectral sensors are deployed in a variety of ways, both above surface, by vessel, aeroplane or satellite, and subsurface, by SCUBA (self-contained underwater breathing apparatus) or autonomous underwater vehicles (AUV).

Hyperspectral imaging is particularly effective in identifying vegetation species and health. Vegetation species are identified by their spectral signatures, as biochemical and structural properties interact with light differently[20]. Further information such as plant health, chlorophyll content and water content can also be captured by analysing spectral patterns.

USES

The main use for hyperspectral imaging is in the mapping and monitoring of BCE due to its effectiveness in identifying vegetation species. This is particularly useful in tidal marshes, where variations in vegetation species and density have led to low quality monitoring by visual imagery. For example, researchers from Université PSL[21] combined visual and hyperspectral imagery from the satellite WorldView-3 (0.31m resolution) with field-based measurements, LiDAR and drone imagery, to create one of the most precise maps of tidal marsh in Beaussais Bay, France. Tangentially, this is a good example of the value of AI in facilitating multi-sensor ecosystem mapping, particularly with hyperspectral data that has specific value and limitations.

Hyperspectral imaging has also been used to good effect in the mapping and monitoring of seagrass. While there have been examples of aerial monitoring[22], these face the aerial challenges of cloud cover and water clarity. More progress has been made in subsurface monitoring, such as by SCUBA (e.g., PlanBlue). Similarly, hyperspectral imaging has been used to map and monitor the underwater ecosystems of kelp[23] and coral reefs[24].

As well as species identification, hyperspectral imagery is used to monitor the health of plants, including the early detection of disease, types of pathogens, as well as non-visible indicators of plant stress[25]. While much of this research has been driven by the agricultural industry, there have been valuable use cases in blue natural capital, such as drone-based hyperspectral imaging used to identify outbreaks of disease in seagrass[26].

Hyperspectral imaging has also been used to good effect in the mapping and monitoring of seagrass.

The future role of hyperspectral imaging is bright due to its precision in monitoring BCE

CHALLENGES

Hyperspectral data is expensive to collect, particularly by aeroplane or SCUBA[27], but also by satellite since high resolution commercial satellites are required. Technical limitations exist and depend on the method, such as dive time or max depth for SCUBA[28]. Additionally, there are the associated constraints of temporal resolution due to cost and time inefficiencies.

The large quantity of data produced by hyperspectral imaging is also a barrier in terms of cost and expertise, with ~100 times the amount of data than equivalent visual imagery[29]. While GEE has limited hyperspectral datasets[30], without data analysis or visualisation platforms acting as an accessible 'front end', hyperspectral data will continue to be inaccessible for non-experts including local stakeholders.

FUTURE

The future role of hyperspectral imaging is bright due to its precision in monitoring BCE. However, its scalability and accessibility is currently limited by cost and inefficiency of data collection and analysis. AUVs have been proposed as "the best platform for UHI (underwater hyperspectral imagery) mapping over large areas (1000 km^2) of seafloor"[31], though this is yet to be demonstrated. Rapidly improving in range, battery life, and deployment, AUVs (e.g., Terradepth[45]) are currently mapping large swaths of the seabed, albeit for offshore construction or military uses, and not yet for mapping of ocean ecosystems.

CASE STUDY:
PLANBLUE[32]

PlanBlue is a seabed mapping company that combines underwater hyperspectral imaging and AI-based automated data processing to map the seafloor. By ground-truthing aerial and satellite imagery, PlanBlue are able to map ecosystems and estimate their carbon sequestration potential. PlanBlue currently focuses on seagrass meadows, with their technology, the DiveRay, deployed by diver or AUV.

[19] www.csr.utexas.edu. (n.d.). Hyperspectral Remote Sensing. [online] Available at: http://www.csr.utexas.edu/projects/rs/hrs/hyper.html.

[20] Glenn, E.P., Huete, A.R., Nagler, P.L. and Nelson, S.G. (2008). Relationship Between Remotely-sensed Vegetation Indices, Canopy Attributes and Plant Physiological Processes: What Vegetation Indices Can and Cannot Tell Us About the Landscape. Sensors, [online] 8(4), pp.2136–2160. doi:https://doi.org/10.3390/s8042136.

[21] Collin, A., Lambert, N. and Etienne, S. (2018). Satellite-based salt marsh elevation, vegetation height, and species composition mapping using the superspectral WorldView-3 imagery. International Journal of Remote Sensing, 39(17), pp.5619–5637. doi:https://doi.org/10.1080/01431161.2018.1466084.

[22] Clarke, K., Hennessy, A., McGrath, A., Daly, R., Gaylard, S., Turner, A., Cameron, J., Lewis, M. and Fernandes, M.B. (2021). Using hyperspectral imagery to investigate large-scale seagrass cover and genus distribution in a temperate coast. Scientific Reports, 11(1). doi:https://doi.org/10.1038/s41598-021-83728-6.

[23] Uhl, F., Bartsch, I. and Oppelt, N. (2016). Submerged Kelp Detection with Hyperspectral Data. Remote Sensing, 8(6), p.487. doi:https://doi.org/10.3390/rs8060487.

[24] QUT Centre for Robotics. (n.d.). UAVs, Hyperspectral Remote Sensing and Machine learning Revolutionizing Reef Monitoring. [online] Available at: https://research.qut.edu.au/qcr/Projects/uavs-hyperspectral-remote-sensing-and-machine-learning-revolutionizing-reef-monitoring/ [Accessed 18 April 2023].

[25] Cheshkova, A.F. (2022). A review of hyperspectral image analysis techniques for plant disease detection and identif ication. Vavilov Journal of Genetics and Breeding, [online] 26(2), pp.202–213. doi:https://doi.org/10.18699/vjgb-22-25.

[26] Yang, B., Hawthorne, T.L., Aoki, L.R., Beatty, D.S., Copeland, T., Domke, L., Eckert, G.L., Gomes, C.P., Graham, O.J., C. Drew Harvell, Hovel, K.A., Hessing-Lewis, M., Harper, L., Mueller, R.S., Rappazzo, B., Reshitnyk, L., Stachowicz, J.J., Tomas, F. and J. Emmett Duffy (2023). Low-Altitude UAV Imaging Accurately Quantifies Eelgrass Wasting Disease From Alaska to California. 50(4). doi:https://doi.org/10.1029/2022gl101985.

[27] Hladik, C., Schalles, J. and Alber, M. (2013). Salt marsh elevation and habitat mapping using hyperspectral and LIDAR data. Remote Sensing of Environment, 139, pp.318–330. doi:https://doi.org/10.1016/j.rse.2013.08.003.

[28] GmbH, D. (n.d.). MarinePlastics - PlaMoWa-Europa-MtecPla. [online] Robotics Innovation Center - DFKI GmbH. Available at: https://robotik.dfki-bremen.de/en/research/projects/marineplastics/ [Accessed 18 April 2023].

[29] www.netguru.com. (n.d.). Why Isn't Hyperspectral Imaging Widely Implemented and How to Change That? [online] Available at: https://www.netguru.com/blog/hyperspectral-imaging-applications.

[30] Google for Developers. (n.d.). Datasets tagged hyperspectral in Earth Engine | Earth Engine Data Catalog. [online] Available at: https://developers.google.com/earth-engine/datasets/tags/hyperspectral [Accessed 24 April 2023].

[31] Johnsen, G., Volent, Z., Dierssen, H., Pettersen, R., Ardelan, M.V., Søreide, F., Fearns, P., Ludvigsen, M. and Moline, M. (2013). 20 - Underwater hyperspectral imagery to create biogeochemical maps of seafloor properties. [online] ScienceDirect. Available at: https://www.sciencedirect.com/science/article/abs/pii/B9780857093417500200 [Accessed 02 May 2023].

[32] Planblue GmbH (2023). Planblue - High-resolution hyperspectral seafloor data. [online] planblue. Available at: https://www.planblue.com/ [Accessed 05 May 2023].

LIDAR

TECHNOLOGY

Bathymetric LiDAR is a method of mapping the seabed using a pulsed laser to measure distances and create accurate 3D maps of the ocean floor. Used in fields from archaeology to autonomous vehicle technology, LiDAR can be deployed in a variety of ways from vessels to aeroplanes to satellites. While sensors vary, typical maximum water depth is 25m[33]. Avoiding the technical limitations of optical imagery, such as water clarity and cloud cover, LiDAR is an efficient monitoring technique for coastal and ocean ecosystems[34].

USES

The main use for LiDAR is in the mapping of ecosystem topography and measurement of above ground or seafloor vegetation[35]. This is particularly valuable since vegetation architecture, including plant height and biomass, are important data points in the estimation of carbon stocks[36]. LiDAR technology has been used to map and subsequently estimate carbon stocks in mangroves, seagrass (e.g., Beneath The Waves and Hexagon), tidal marsh, kelp[37] and coral reefs[38]. Since LiDAR has quite a specific value proposition, accurately measuring topography and plant height, it is often used in a multi-sensor approach. For example, Beneath The Waves have used methods such as satellite imagery to identify the seagrass meadows to be studied in more detail by LiDAR.

The future role of LiDAR is in the scalable measurement of BCE vegetation for more accurate estimations of carbon stocks.

CHALLENGES

LiDAR is highly suitable for mangroves and seagrass meadows, particularly in cases where equipment is highly calibrated such as with Beneath The Waves with technology partners Hexagon, but is less effective in measuring the height of sparse small plants such as herbaceous vegetation (small plants with no woody stem) found in tidal marshes.

LiDAR data is expensive to collect, particularly by popular airborne methods, both with respect to budget and preparation. Similarly to hyperspectral imagery, these cost considerations combined with technical barriers of data collection and analysis, mean that LiDAR data is not accessible to non-experts including local stakeholders.

FUTURE

The future role of LiDAR is in the scalable measurement of BCE vegetation for more accurate estimations of carbon stocks. As we see from Beneath The Waves, airborne LiDAR has the potential to cover thousands of square kilometres in a matter of days, particularly when combined with other complimentary sensors.

CASE STUDY:
BENEATH THE WAVES AND HEXAGON[39]

Beneath The Waves, GIS company Hexagon and the Bahamian Government, have used airborne bathymetric LiDAR to map, monitor and quantify seagrass meadows in the Bahamas. With LiDAR data taken by aeroplane at 500m, thousands of square kilometres of seagrass were mapped in days. LiDAR data was fed into AI programs to map seagrass meadows' seabed types, vegetation species and density, with sub-metre resolution at an accuracy of more than 95 per cent. Combined with satellite imagery and field-based core samples, carbon values could be estimated, providing a map and quantification of seagrass meadows and their carbon stock.

[33] leica-geosystems.com. (n.d.). Mapping underwater terrain with bathymetric LiDAR. [online] Available at: https://leica-geosystems.com/en-gb/case-studies/natural-resources/mapping-underwater-terrain-with-bathymetric-lidar [Accessed 20 May 2023].

[34] Letard, M., Collin, A., Lague, D., Corpetti, T., Pastol, Y., Ekelund, A., Pergent, G. and Costa, S. (2021). Towards 3D Mapping of Seagrass Meadows with Topo-Bathymetric Lidar Full Waveform Processing. [online] IEEE Xplore. doi:https://doi.org/10.1109/IGARSS47720.2021.9554262.

[35] Asner, G.P., Hughes, R.F., Mascaro, J., Uowolo, A.L., Knapp, D.E., Jacobson, J., Kennedy-Bowdoin, T. and Clark, J.K. (2011). High-resolution carbon mapping on the million-hectare Island of Hawaii. Frontiers in Ecology and the Environment, 9(8), pp.434–439. doi:https://doi.org/10.1890/100179.

[36] Hickey, S.M., Callow, N.J., Phinn, S., Lovelock, C.E. and Duarte, C.M. (2018). Spatial complexities in aboveground carbon stocks of a semi-arid mangrove community: A remote sensing height-biomass-carbon approach. Estuarine, Coastal and Shelf Science, 200, pp.194–201. doi:https://doi.org/10.1016/j.ecss.2017.11.004.

[37] Young, M., Ierodiaconou, D. and Womersley, T. (2015). Forests of the sea: Predictive habitat modelling to assess the abundance of canopy forming kelp forests on temperate reefs. Remote Sensing of Environment, 170, pp.178–187. doi:https://doi.org/10.1016/j.rse.2015.09.020.

[38] Collin, A., Ramambason, C., Pastol, Y., Casella, E., Rovere, A., Thiault, L., Espiau, B., Siu, G., Lerouvreur, F., Nakamura, N., Hench, J.L., Schmitt, R.J., Holbrook, S.J., Troyer, M. and Davies, N. (2018). Very high resolution mapping of coral reef state using airborne bathymetric LiDAR surface-intensity and drone imagery. International Journal of Remote Sensing, 39(17), pp.5676–5688. doi:https://doi.org/10.1080/01431161.2018.1500072.

[39] Hexagon. (n.d.). Beneath-The-Waves-and-Hexagon-win-Geospatial-World. [online] Available at: https://hexagon.com/company/newsroom/press-releases/2023/beneath-the-waves-and-hexagon-win-geospatial-world [Accessed 14 April 2023].

SONAR

TECHNOLOGY

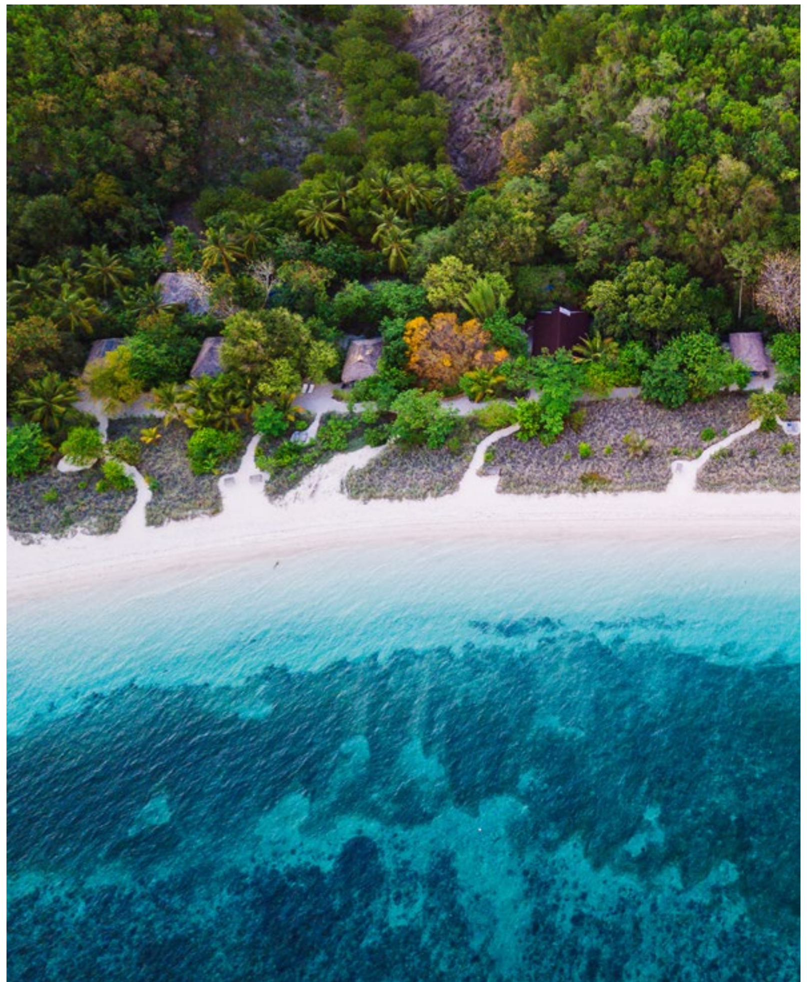
Sonar mapping, also known as seismo-acoustic mapping, is a technique to map the seafloor and sub-seafloor with sound waves. The two available technologies are side-scan sonar and echosounders. Side-scan sonar uses basic sound propagation to measure distances and map seabed topography. Limited in coverage, water depth and at risk of missing low levels of vegetation, echosounders have emerged as a higher-resolution alternative. Still using sonar technology, echosounders' beams are able to infiltrate metres below the seabed, providing valuable information on soil qualities including carbon value, as well as seabed topography and vegetation cover.

USES

Sonar is used to map BCE, particularly seagrass, due to the subsurface nature of the ecosystem and associated challenges for optical imagery. A good example of this is Greene[40], who created a high resolution (2.5cm resolution) map of seagrass meadows using affordable consumer-grade side-scan sonar technology combined with satellite imagery. Similarly, echosounders have been deployed for kelp mapping[41]. Taking this further, echosounder technology has been deployed to not only map seagrass extent, but also estimate carbon stocks by combining sonar data with soil sediment cores[42], providing high quality data over large distances.

Aside from ecosystem mapping and carbon stock estimation, echosounders have also been deployed to monitor other characteristics of seagrass meadows, such as the identification of invasive urchins[43].

Importantly, due to the seabed being the largest pool of carbon stock in the world[44], echosounders have also been deployed to map seabed sediment and estimate carbon stocks. For example, Hunt[45] has combined physical sampling with echosounder mapping to improve the quality of current soil sediment carbon value predictions by 14 per cent. Sediment type, particularly sediment granularity (fine to course), was used as an identifier of carbon value up to two metres below the seabed.



CHALLENGES

Sonar technology is currently deployed by vessel, including large research vessels to small day boats, making it variably cost and time consumptive. It also has restricted spatial coverage. As a result, sonar technologies have feasibility for small and medium-scale (<1000 hectares) projects, but not for large country-scale mapping where satellite is the only feasible option at the required scale. As with other sensors, AUV technology has been presented as an attractive future transport method, particularly since many AUVs currently have echosounders in their sensor suite (e.g., Terradepth[46]).

FUTURE

The future role of sonar mapping, particularly by echosounder, is exciting due to its ability to provide information on soil carbon stock, seafloor topography and vegetation cover. While this technology is in its infancy, with limited research in seagrass and for soil sediment carbon stocks, it has the potential for soil carbon estimation in mangroves and tidal marsh[47]. As with hyperspectral imagery, there is significant potential for scale by AUV.

CASE STUDY:
SAVE POSIDONIA PROJECT[48]

The Save Posidonia Project used side-scan sonar, supported by drone and SCUBA imagery, to identify and map seagrass meadows in Ibiza. This map was used to create an app to guide boats away from anchoring on seagrass meadows.

[40] Side scan sonar: A cost-efficient alternative method for measuring seagrass cover in shallow environments. (2018). Estuarine, Coastal and Shelf Science, [online] 207, pp.250–258. doi:https://doi.org/10.1016/j.ecss.2018.04.017.

[41] Bennion, M., Fisher, J., Yesson, C. and Brodie, J. (2018). Remote Sensing of Kelp (Laminariales, Ochrophyta): Monitoring Tools and Implications for Wild Harvesting. Reviews in Fisheries Science & Aquaculture, 27(2), pp.127–141. doi:https://doi.org/10.1080/23308249.2018.1509056.

[42] Monnier, B., Pergent, G., Mateo, M.Á., Carbonell, R., Clabaut, P. and Pergent-Martini, C. (2021). Sizing the carbon sink associated with Posidonia oceanica seagrass meadows using very high-resolution seismic reflection imaging. Marine Environmental Research, 170, p.105415. doi:https://doi.org/10.1016/j.marenvres.2021.105415.

[43] Carnell, P.E., Ierodiaconou, D., Atwood, T.B. and Macreadie, P.I. (2020). Overgrazing of Seagrass by Sea Urchins Diminishes Blue Carbon Stocks. Ecosystems, 23(7), pp.1437–1448. doi:https://doi.org/10.1007/s10021-020-00479-7.

[44] Atwood, T.B., Witt, A., Mayorga, J., Hammill, E. and Sala, E. (2020). Global Patterns in Marine Sediment Carbon Stocks. Frontiers in Marine Science, 7. doi:https://doi.org/10.3389/fmars.2020.00165

[45] Hunt, C.A., Demšar, U., Marchant, B., Dove, D. and Austin, W.E.N. (2021). Sounding Out the Carbon:: The Potential of Acoustic Backscatter Data to Yield Improved Spatial Predictions of Organic Carbon in Marine Sediments. Frontiers in Marine Science, [online] 8(756400). doi:https://doi.org/10.3389/fmars.2021.756400.

[46] Terradepth. (n.d.). Homepage. [online] Available at: https://www.terradepth.com/.

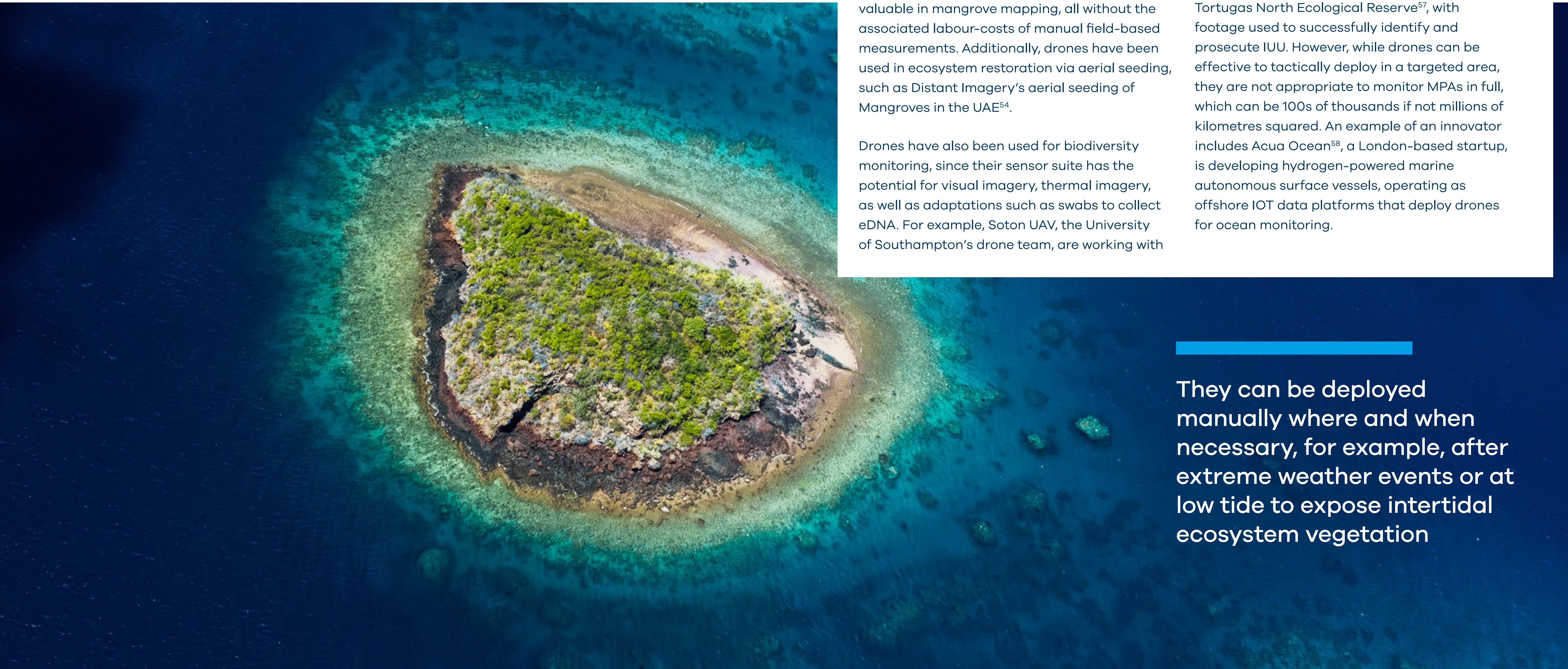
[47] ET, U. and JE, E. (2016). Comparison of the Characteristics of Low Velocity Layer (LVL) in the Mangrove Swamp and in the Upper Flood Plain Environments in the Niger Delta, using Seismic Refraction Methods. Journal of Geology & Geophysics, [online] 5(4). doi:https://doi.org/10.4172/2381-8719.1000248.

[48] Oceanic Global. (n.d.). Posidonia Maps Project. [online] Available at: https://oceanic.global/projects/posidonia-maps-project/ [Accessed 01 May 2023].

DRONES

TECHNOLOGY

Drones (UAVs) are machines that fly without a pilot carrying sensors[49]. As with other technologies that transport sensors (e.g., satellite), rather than being as a sensor themselves (e.g., LiDAR), drones vary in sensor suite and functionality. Sensors found on drones include visual, thermal and hyperspectral imagery. They can be deployed manually where and when necessary, for example, after extreme weather events or at low tide to expose intertidal ecosystem vegetation[50].



USES

Drones have been used for small-scale BCE monitoring due to their ease of deployment in targeted locations and high resolution data, including seagrass[51], mangroves, tidal marsh and kelp[52]. For example, drones have been used in tidal marsh mapping and monitoring, with researchers from the University of South Carolina[53] using imagery and AI to create detailed maps of marsh vegetation. Due to the high resolution of data, drones can also collect detailed information such as tree heights and stem diameters, particularly valuable in mangrove mapping, all without the associated labour-costs of manual field-based measurements. Additionally, drones have been used in ecosystem restoration via aerial seeding, such as Distant Imagery's aerial seeding of Mangroves in the UAE[54].

Drones have also been used for biodiversity monitoring, since their sensor suite has the potential for visual imagery, thermal imagery, as well as adaptations such as swabs to collect eDNA. For example, Soton UAV, the University of Southampton's drone team, are working with Marwell Wildlife to develop drones for wildlife identification, monitoring and conservation. Another great example of innovation is Snotbot[56], a drone developed by Ocean Alliance that flies above whales collecting samples of eDNA from their blow.

In MPA management and protection, drones have been deployed to detect and collect evidence of illegal activity. For example, the Florida Fish and Wildlife Conservation Commission has used drones to monitor the Tortugas North Ecological Reserve[57], with footage used to successfully identify and prosecute IUU. However, while drones can be effective to tactically deploy in a targeted area, they are not appropriate to monitor MPAs in full, which can be 100s of thousands if not millions of kilometres squared. An example of an innovator includes Acua Ocean[58], a London-based startup, is developing hydrogen-powered marine autonomous surface vessels, operating as offshore IOT data platforms that deploy drones for ocean monitoring.

They can be deployed manually where and when necessary, for example, after extreme weather events or at low tide to expose intertidal ecosystem vegetation

CHALLENGES

Drones are affordable for researchers and managers from high-income countries. This is particularly the case when compared to expensive alternatives, such as drones reporting to decrease the cost of manual mangrove biomass measurements in Australia by USD $35,000 per hectare[59]. However, this is not the case of local stakeholders from low-income countries where commercial imagery drones, even at the recent prices of USD $300, are prohibitive. However, lessons can be learnt from others, such as Drones for Justice, a project by Indonesian NGO the Swandiri Institute to co-own drones with local community members to educate and empower them to monitor illegal activity by palm oil and mining companies[60]. Also, Distant Imagery are working with low-income stakeholders on upcycled and 3D printed drones[61].

FUTURE

Drones have proven to be useful in ocean environments due to their ease of deployment, high resolution, as well affordability for high income stakeholders. Cost and technical limitations still limit access to low-income local stakeholders, where technical and financial innovation is needed to allow access to this valuable technology.

[49] Ministry of Defence (2017). Drones – are you flying yours safely? (and legally?). [online] GOV.UK. Available at: https://www.gov.uk/government/news/drones-are-you-flying-yours-safely-and-legally.

[50] Saccomanno, V.R., Bell, T., Pawlak, C., Stanley, C.K., Cavanaugh, K.C., Hohman, R., Klausmeyer, K.R., Cavanaugh, K., Nickels, A., Hewerdine, W., Garza, C., Fleener, G. and Gleason, M. (2022). Using unoccupied aerial vehicles to map and monitor changes in emergent kelp canopy after an ecological regime shift. Remote Sensing in Ecology and Conservation. doi:https://doi.org/10.1002/rse2.295.

[51] Carpenter, S., Byfield, V., Felgate, S.L., Price, D.M., Andrade, V., Cobb, E., Strong, J., Lichtschlag, A., Brittain, H., Barry, C., Fitch, A., Young, A., Sanders, R. and Evans, C. (2022). Using Unoccupied Aerial Vehicles (UAVs) to Map Seagrass Cover from Sentinel-2 Imagery. Remote Sensing, 14(3), p.477. doi:https://doi.org/10.3390/rs14030477.

[52] Remote Sensing in Ecology and Conservation Blog. (2022). Using drones to map and monitor changes in kelp forest canopy after an ecological regime shift. [online] Available at: https://rsecjournal.blog/2022/09/22/using-drones-to-map-and-monitor-changes-in-kelp-forest-canopy-after-an-ecological-regime-shift/ [Accessed 10 May 2023].

[53] Morgan, G. (2022). sUAS and Deep Learning for High-Resolution Monitoring of Tidal Marshes in Coastal South Carolina. Theses and Dissertations. [online] Available at: https://scholarcommons.sc.edu/etd/6777/ [Accessed 26 April 2023].

[54] Distant Imagery. (n.d.). Drone Habitat Restoration. [online] Available at: https://www.distantimagery.com/copy-of-our-engineering [Accessed 24 April 2023].

[55] www.sotonuav.uk. (n.d.). Soton UAV. [online] Available at: https://www.sotonuav.uk/ [Accessed 03 May 2023].

[56] Ocean Alliance. (2018). SnotBot. [online] Available at: https://whale.org/snotbot/.

[57] thefishsite.com. (n.d.). The Use of Drones for Tackling Illegal Fishing. [online] Available at: https://thefishsite.com/articles/the-use-of-drones-for-tackling-illegal-fishing.

[58] ACUA Ocean. (n.d.). Uncrewed Surface Vessel. [online] Available at: https://www.acua-ocean.com [Accessed 22 April 2023].

[59] Navarro, A., Young, M., Allan, B., Carnell, P., Macreadie, P. and Ierodiaconou, D. (2020). The application of Unmanned Aerial Vehicles (UAVs) to estimate above-ground biomass of mangrove ecosystems. Remote Sensing of Environment, 242, p.111747. doi:https://doi.org/10.1016/j.rse.2020.111747.

[60] Radjawali, I. and Pye, O. (2017). Drones for justice: inclusive technology and river-related action research along the Kapuas. Geographica Helvetica, 72(1), pp.17–27. doi:https://doi.org/10.5194/gh-72-17-2017.

[61] www.youtube.com. (n.d.). Question 1 - New Technologies to Support Blue Forests Conservation. [online] Available at: https://youtu.be/AhbVITHnl8I [Accessed 12 May 2023].

[62] Distant Imagery. (n.d.). Customized Drones | Aerial Analysis | United Arab Emirates. [online] Available at: https://www.distantimagery.com/ [Accessed 08 May 2023].

CASE STUDY:
DISTANT IMAGERY[62]

Distant Imagery Solutions, a UAE-based drone digital imagery company, have utilised drones in both the monitoring and restoration of mangroves. For monitoring, drones with near-infrared capability are used, combined with the Normalised Difference Vegetation Index (NDVI) to identify and quantify the density of healthy vegetation. Illustrating the versatility of drones, they have also been used in mangrove habitat restoration through aerial seeding.

COMPUTER VISION

TECHNOLOGY

Computer vision is a field of AI in which computer systems derive information from images and videos. "If AI enables computers to think, computer vision enables them to see, observe and understand."[63]

USES

Computer vision has been deployed to map and monitor seagrass. For example, Tidal, an underwater camera and computer vision company from Alphabet, have applied their aquaculture technology to seagrass. Underwater cameras are used to take images of the seabed, with machine vision then creating 3D maps of topography and seagrass. Having taken seagrass seabed sediment cores, reliable estimates for carbon stock are given. While they envision creating AUVs for their technology, it is currently transported by SCUBA or small vessels. Tidal's stated vision is for carbon data reliable enough for scalable verification[64].

Visual inspection is used to identify, monitor and track marine biodiversity. Traditionally this has been done manually by field-based image and video, manually analysed by humans. However, AI has become prevalent due to optimised cost and time efficiency, as well as humans being more prone to error than identification algorithms[65]. AI has been used for fish species identification, count, behaviour recognition and biomass estimation[66]. Much technology has come from aquaculture, following development from aquaculture-tech companies like Tidal, Ecotone and Aquabyte, with specific biodiversity related capabilities emerging from Stream Ocean.

Computer vision and machine learning has also allowed for the 3D mapping of coral reefs. Technology in close proximity to the reef can collect more granular data, including drones or underwater vehicles. This allows for higher quality spatial and temporal resolution, however, the compromise is with geographic and cost limitations. Here, the most common data source is optical imagery, often combined with photogrammetry, extracting 3D information from imagery. Reef Check, a French reef conservation charity, have used Scuba-based GoPro footage of coral reefs to create 3D maps of reefs using photogrammetry, partnering with the 3D modelling company Pix4D. For image collection, technology has advanced to allow for long term in situ monitoring of coral. View Into the Blue[67] is an underwater camera company, who have developed time lapse camera systems to record coral bleaching events over months.

CASE STUDY:
STREAM OCEAN[70]

Stream Ocean deploys autonomous underwater camera systems for real-time monitoring and analysis of ocean conditions, biodiversity data and visual content, accessible to non-experts on a desktop dashboard. Stream Ocean is currently working with coral restoration projects in the Maldives but is increasing its project base to include offshore renewables and other marine environments.

CHALLENGES

Challenges are faced in underwater machine vision due to the nature of the environment, including; (i) underwater images are degraded due to the scattering effect of light passing through water; (ii) exploration camera equipment imposing limitations on image resolution; (iii) small marine organisms are difficult to detect, particularly with dense distribution[68]; (iv) complex and fluid background structures[69].

Machine vision cameras in remote locations away from infrastructure such as electricity sources or mobile networks face the challenge of connectivity, particularly considering the large data demands of machine vision. Innovators such as Stream Ocean are overcoming these challenges with on-site cameras, data processing kit and solar powered connection tower.

FUTURE

The future role of computer vision in blue natural capital is in the scalable monitoring of ecosystems and their marine life. Computer vision has the potential to revolutionise ecosystem monitoring by not only bearing the burden of the vast amounts of collected data but also transforming the quality of insights taken from this data.

[63] www.ibm.com. (n.d.). What is Computer Vision? | IBM. [online] Available at: https://www.ibm.com/topics/computer-vision#:~:text=Resources-.

[64] MIT Technology Review. (n.d.). Inside Alphabet X's new effort to combat climate change with seagrass. [online] Available at: https://www.technologyreview.com/2022/11/09/1062847/inside-alphabet-xs-new-effort-to-combat-climate-change-with-seagrass/.

[65] Saleh Ibrahim, Y., Khalid Al-Azzawi, W., Hamad Mohamad, A.A., Nouri Hassan, A. and Meraf, Z. (2022). Perception of the Impact of Artificial Intelligence in the Decision-Making Processes of Public Healthcare Professionals. Journal of Environmental and Public Health, [online] 2022, p.8028275. doi:https://doi.org/10.1155/2022/8028275.

[66] Abinaya, N.S., Susan, D. and Sidharthan, R.K. (2022). Deep learning-based segmental analysis of fish for biomass estimation in an occulted environment. Computers and Electronics in Agriculture, 197, p.106985. doi:https://doi.org/10.1016/j.compag.2022.106985.

[67] View Into The Blue®. (n.d.). View Into The Blue®. [online] Available at: https://www.viewintotheblue.com/.

[68] Meng Joo Er, Chen, J., Zhang, Y. and Gao, W. (2023). Research Challenges, Recent Advances, and Popular Datasets in Deep Learning-Based Underwater Marine Object Detection: A Review. [online] 23(4), pp.1990–1990. doi:https://doi.org/10.3390/s23041990.

[69] Gracias, N., Rafael Galindo Garcia, Campos, R., Hurtos, N., Prados, R., Asm Shihavuddin, Tudor Nicosevici, Armagan Elibol, Neumann, L. and Escartín, J. (2017). Application Challenges of Underwater Vision. doi:https://doi.org/10.1002/9781118868065.ch7.

[70] www.streamocean.io. (n.d.). Stream Ocean - Making the invisible visible. [online] Available at: https://www.streamocean.io/ [Accessed 16 May 2023].

eDNA

TECHNOLOGY

Environmental DNA (eDNA) refers to DNA released by living things into their environment. This encompasses all marine life, from bacteria to whales, and can be found in mucus, faeces and other material. While DNA can be analysed from other sources, such as soil and air, in marine environments water samples are used. eDNA has the benefits of being non-intrusive to organisms, also increasing the chance of collecting data on organisms that shy away from research equipment.

USES

eDNA is used for biodiversity monitoring, with analysis approaches for species presence, community structure and relative DNA and species abundance. Using these methods, scientists can; (i) detect specific species, particularly useful for the identification and monitoring of endangered or invasive species; such as the identification of the critically endangered Yangtze Finless Porpoise by researchers in China[71]; (ii) estimate biodiversity and community structure, such as the monitoring of otters, seals and sea lions associated with kelp forests in California[72]; (iii) infer information about the dynamics of the ecosystem including the food web[73].

Showing the versatility of eDNA as a research method, other uses include in water quality monitoring by identifying harmful bacteria, and in fisheries management, to inform catch locations and methods.

CHALLENGES

eDNA faces certain limitations as a research method, many of which are exaggerated in the ocean and other water bodies[74]; (i) eDNA detection can vary depending on the species, species abundance and environment condition, with examples of low abundance species mis-identified as non-present[75]; (ii) Temporal resolution is challenging, since eDNA can give evidence of species presence at a specific time, but since eDNA degrades over time, particularly in ocean and water bodies, it may not accurately represent species presence or absence; (iii) Spatial resolution is challenging, particularly in dynamic ocean and coastal environments, with movement of eDNA disrupting precise location tracking, as seen by eDNA samples found at both a few metres[76] and twenty kilometres[77] of known species sites in rivers.; (iv) eDNA cannot detect all species due to lack of DNA reference databases, particularly in less researched ocean and coastal environments[78].

Crucially, eDNA is also limited by time-lag, since samples must be adequately collected, transported and analysed in a controlled lab environment, which brings significant associated costs with such a sensitive and technical research method.

Responding to the above challenges, eRNA has emerged as a complementary technology. eRNA is similar to eDNA, but is transcribed from active enhancers, meaning they reflect cell state and function[79]. Practically, this means that eRNA can infer the physiological state of organisms, such as sex, age and health[80], giving more precise information about specific organisms, communities and ecosystems. Moreover, innovators such as EQO[81] are improving the already fast turnover rate of eRNA with portable equipment.

FUTURE

The future role of eDNA is in evidence-based biodiversity monitoring, with useful data collected on species presence, biodiversity estimates, as well as further information about ecosystem dynamics. Progress needs to be made in the accessibility of eDNA, with cost and technical barriers significant for non-experts and local stakeholders.

CASE STUDY:
SOLENT SEASCAPE PROJECT[82]

Blue Marine Foundation is using eDNA in their Solent Seascape Project for marine biodiversity monitoring. Working with Plan Vivo, eDNA data will provide evidence for biodiversity uplift to determine biodiversity credits. Combined with habitat maps, machine learning will be used to predict species behaviour to inform habitat, fisheries and MPA management.

71 Qu, C. and Stewart, K.A. (2019). Evaluating monitoring options for conservation: comparing traditional and environmental DNA tools for a critically endangered mammal. The Science of Nature, 106(3-4). doi:https://doi.org/10.1007/s00114-019-1605-1.

72 Port, J.A., O'Donnell, J.L., Romero-Maraccini, O.C., Leary, P.R., Litvin, S.Y., Nickols, K.J., Yamahara, K.M. and Kelly, R.P. (2015). Assessing vertebrate biodiversity in a kelp forest ecosystem using environmental DNA. Molecular Ecology, 25(2), pp.527–541. doi:https://doi.org/10.1111/mec.13481.

73 oceanexplorer.noaa.gov. (n.d.). Exploration Tools: Environmental DNA: NOAA Office of Ocean Exploration and Research. [online] Available at: https://oceanexplorer.noaa.gov/technology/edna/edna.html.

74 Roussel, J.-M., Paillisson, J.-M., Tréguier, A. and Petit, E. (2015). The downside of eDNA as a survey tool in water bodies. Journal of Applied Ecology, 52(4), pp.823–826. doi:https://doi.org/10.1111/1365-2664.12428.

75 Tréguier, A., Paillisson, J.-M., Dejean, T., Valentini, A., Schlaepfer, M.A. and Roussel, J.-M. (2014). Environmental DNA surveillance for invertebrate species: advantages and technical limitations to detect invasive crayfishProcambarus clarkiiin freshwater ponds. Journal of Applied Ecology, 51(4), pp.871–879. doi:https://doi.org/10.1111/1365-2664.12262.

76 Pilliod, D.S., Goldberg, C.S., Arkle, R.S. and Waits, L.P. (2013). Factors influencing detection of eDNA from a stream-dwelling amphibian. Molecular Ecology Resources, 14(1), pp.109–116. doi:https://doi.org/10.1111/1755-0998.12159.

77 Deiner, K. and Altermatt, F. (2014). Transport Distance of Invertebrate Environmental DNA in a Natural River. PLoS ONE, 9(2), p.e88786. doi:https://doi.org/10.1371/journal.pone.0088786.

78 Wee, A.K.S., Iii, S.G.S., Hui, A.T.Y., Basyuni, M., Sivakumar, K., Fall, J., Habib, K.A., Isowa, Y., Leopardas, V., Peer, N., Artigas-Ramirez, M.D., Ranawana, K., Sivaipram, I., Suleiman, M. and Kajita, T. (2023). Prospects and challenges of environmental DNA (eDNA) metabarcoding in mangrove restoration in Southeast Asia. [online] www.apn-gcr.org. Available at: https://www.apn-gcr.org/publication/prospects-and-challenges-of-environmental-dna-edna-metabarcoding-in-mangrove-restoration-in-southeast-asia/ [Accessed 12 May 2023].

79 Arnold, P.R., Wells, A.D. and Li, X.C. (2020). Diversity and Emerging Roles of Enhancer RNA in Regulation of Gene Expression and Cell Fate. Frontiers in Cell and Developmental Biology, 7. doi:https://doi.org/10.3389/fcell.2019.00377.

80 Yates, M.C., Derry, A.M. and Cristescu, M.E. (2021). Environmental RNA: A Revolution in Ecological Resolution? Trends in Ecology & Evolution, [online] 36(7), pp.601–609. doi:https://doi.org/10.1016/j.tree.2021.03.001.

81 EQO. (n.d.). Biotech Tools for Aquatic Ecosystem Health & Management | EQO | Austin, TX. [online] Available at: https://www.eqo.life/ [Accessed 18 May 2023].

82 Blue Marine Foundation. (n.d.). Solent Seascape Project. [online] Available at: https://www.bluemarinefoundation.com/projects/solent-seascape-project/ [Accessed 20 May 2023].

CONCLUSION

Blue Marine Foundation is delighted to play a role in supporting, deploying and testing innovative new technology in our conservation and restoration projects. We are actively seeking new technology partners from inside and outside the field and look forward to a future when bigger companies bring their expertise and manufacturing capability to answering these questions and solving the global challenge of better understanding the marine environment.

Our hope is that this technology review can be helpful to other blue natural capital projects and the different stakeholder groups considering these projects. There are silos between practitioners, investor, government and regulators. Streams of accurate data can help to overcome these silos and make these projects easily intelligible for a broader audience.

The impact of innovative technology showcased in the report is clear, from LiDAR mapping vast seagrass meadows in the Bahamas to GEEMMM making satellite technology accessible to local communities.

There is no sign of this slowing, with innovative technologies and foundational research continuing to emerge. Even during the writing of this report, pioneering research was published estimating fish stocks using machine learning and satellite imagery[83], and Blue Marine Foundation will be deploying innovative benthic chambers for nutrient and nitrate data in the Solent.

The ocean faces multiple human pressures, from climate change to overfishing, and while there's no silver bullet technology, innovation continues to help scientists, governments and other stakeholders map, monitor and protect the ocean and the natural capital within it.

[83] McClanahan, T.R., D'Agata, S., Graham, N.A.J., Kodia, M.A. and Maina, J.M. (2023). Multivariate environment-fish biomass model informs sustainability and lost income in Indian Ocean coral reefs. Marine Policy, [online] 152, p.105590. doi:https://doi.org/10.1016/j.marpol.2023.105590.

BLUE CARBON ECOSYSTEM MATRIX

Overview of aforementioned technologies and their applicability to BCE. Focus is on small to medium-scale projects, since satellite technology is the only viable option for large-scale projects. Colour coordination refers to recommendations for use: HIGH, MEDIUM, LOW.

	Mangroves	Seagrass	Salt marsh	Macroalgae	Seabed sediment
Satellite imagery	**Data:** Presence, variety, density, height **Cost:** Low **Notes:** Less effective for small-scale	**Data:** Presence **Cost:** Low **Notes:** Less effective in low water clarity	**Data:** Presence, variety, density **Cost:** Low **Notes:** Temporal resolution needed for dynamic ecosystem	**Data:** Presence **Cost:** Low **Notes:** Temporal resolution needed for dynamic ecosystem	N/A
Hyperspectral imagery	**Data:** Presence, variety, density, health **Cost:** Medium **Notes:** Airborne	**Data:** Presence, variety, density, health **Cost:** High **Notes:** Underwater and effective combined with other sensors	**Data:** Presence, variety, density, health **Cost:** Medium **Notes:** Airborne and effective with other sensors	**Data:** Presence **Cost:** Medium **Notes:** Airborne and less effective in low water clarity	N/A
LiDAR	**Data:** Height **Cost:** High **Notes:** Effective with other sensors	**Data:** Presence, height **Cost:** High **Notes:** Effective with other sensors	**Data:** Presence, height **Cost:** High **Notes:** Effective with other sensors	**Data:** Presence **Cost:** High **Notes:** Effective with other sensors	N/A
Sonar	**Data:** Presence, density, height, soil carbon **Cost:** High **Notes:** Echosounder for soil carbon untested in mangroves	**Data:** Presence, density, height, soil carbon **Cost:** High **Notes:** Echosounder effective for soil carbon data	**Data:** Presence, density, height, soil carbon **Cost:** High **Notes:** Echosounder for soil carbon untested in salt marsh	**Data:** Presence, density **Cost:** High **Notes:** Soil carbon less applicable to kelp	**Data:** Soil carbon **Cost:** High **Notes:** Echosounder effective for soil carbon data
Drones	**Data:** Presence, variety, density, height **Cost:** Medium **Notes:** Recommended for small-scale	**Data:** Presence, variety, density, height **Cost:** Medium **Notes:** Recommended for small-scale	**Data:** Presence, variety, density, height **Cost:** Medium **Notes:** Recommended for small-scale	**Data:** Presence, variety, density **Cost:** Medium **Notes:** Recommended for small-scale	N/A

ABBREVIATIONS

AI	Artificial intelligence
AUV	Autonomous underwater vehicle
BCE	Blue carbon ecosystem
eDNA	Environmental DNA
IOT	Internet of things
IUU	Illegal, unreported, and unregulated fishing
LiDAR	Light detection and ranging
MPA	Marine protected areas
MRV	Monitoring, reporting and verification
NDC	Nationally determined contribution
NDVI	Normalised difference vegetation index
SAR	Synthetic aperture radar
SCUBA	Self contained underwater breathing apparatus

GLOSSARY

Biodiversity
The variety of life found in a place, including animals, plants, fungi and microorganisms.

Biodiversity credits
Unit of biodiversity value created through conservation activities that have led to a biodiversity gain.

Blue carbon
The carbon stored in coastal and marine ecosystems, particularly in algae, mangroves, tidal marshes and seagrasses, in their biomass and sediments. Blue carbon also relates to carbon stored in seabed sediments, fish and shellfish.

Blue natural capital
Natural capital found in ocean and coastal environments.

Carbon credits
Unit of carbon value from climate action projects that have led to reduction, removal or avoidance of greenhouse gas emissions.

Carbon stock
The total amount of organic carbon stored in a blue carbon ecosystem or carbon pool(s) of a known size.

Nationally determined contributions
Commitments of each country to reduce their greenhouse gas emissions.

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