Carbon Footprints

Opinion

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Use of emerging technologies to help measure fjordic biodiversity and blue carbon: mini-manned submarines and autonomous underwater vehicle swarms

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Abstract

Meaningful protection of global oceans lags far behind that of land and has taken little consideration of climate mitigation potential to date (such as through assessment of blue carbon stocks and change). With the new emphasis on synergistic approaches to the identification and conservation of both carbon- and species- rich habitats, we need much better knowledge of the geography and status of blue carbon habitats beyond coastal wetlands. In subpolar and polar regions, some blue carbon habitats are still emerging and work as negative (mitigating) feedback on climate change, yet remain unprotected despite strong evidence of threat overlap. Scientific research expeditions are gradually increasing our understanding, but appropriate vessels are a limiting factor due to high costs and carbon footprints. Even when available such vessels cannot access all areas (e.g., remote fjords with sills) and may struggle to measure certain aspects of habitats (e.g., steep or vertical surfaces). New technologies and opportunities have advanced to aid some of these problems, and here, two of them are considered, mini-manned submersibles and autonomous underwater vehicles. These two platforms have both become much more available and affordable (through novel partnerships) while also being much more scientifically capable. This technology has the potential to reduce the carbon footprint of science and particularly aid in assessing biology and environment status and change on steep sides, such as fjord walls.

Keywords: Submersible, autonomous underwater vehicle, fjord, marine biodiversity, quantification

INTRODUCTION

Recent United Nations Climate Change Conference of Parties (COP) meetings have emphasized just how urgent meaningful action on climate change is. Urgent and deep emissions cuts are very clearly required, but there are other extremely helpful activities that could and should be undertaken alongside direct greenhouse gas reductions. The crisis of anthropogenically-driven climate change is intertwined with that of nature loss[1]. Nature contributes to human health in many crucial ways[2] and, importantly, to climate regulation[3]. Synergistic action and solutions to both crises tend to be more effective and long-lasting. These include so-called nature-based solutions[4,5]. Nature-based solutions focus on identifying, protecting, and fostering services and functions already provided by ecosystems that help to mitigate climate change. These include the protection of species- and carbon-rich habitats to avoid losing highly efficient natural carbon sinks. In the sea, habitats that contribute significantly to the capture of carbon from the atmosphere, and its subsequent storage and sequestration are termed blue carbon habitats (see Macreadie *et al.*)[6]. Despite considerable discussion and raised profile, such vital protective actions across global ocean habitats have lagged far behind those on land[7]. Marine Protected Areas (MPA) are often designated and implemented without consideration of their blue carbon potential. Regular monitoring of these MPAs rarely occurs, owing to the lack of resources, and thus it is often unclear whether the hitherto establishment of MPAs offers solutions to the current crises[8]. More problematic still is that there is a strong overlap between carbon-rich hotspots in ocean habitats (measured in terms of pelagic carbon export to the seafloor) and threats to these habitats, e.g., from fishing[9]. Thus, the current status could be summarised as (1) a strong requirement and call for better knowledge and protection of species- and carbon-rich habitats; (2) strong evidence of threat overlap with such areas; and (3) little evidence of response in designation or implementation of threat-mitigating protection to these key oceanic hotspots.

Prioritisation for the designation of such hotspots should focus on near-intact ecosystems, which act as the most efficient carbon pathways to sequestration[10] and which of the degraded systems are most cost-effective and realistic to restore[11]. There are important blue carbon habitats that have received considerable attention, typically low-latitude mangrove swamps[12] and seagrass meadows[13]. However, these occupy a small (~4.1 and ~4.4%, respectively) and declining space[14]. Carbon storage and burial contributions of marshes and macroalgal forests (seaweed) are more difficult to quantify as much of their productivity is exported through oceanic dispersal. However, both systems are increasingly being realized as very important and the area they are occupying can be enhanced or their standing stock increased[15]. Other marine habitats can be important too, for example, fjords. These may occupy just 0.3% of our planet, but they accumulate a massive 11% of marine carbon burial globally[16]. Furthermore, glacier retreat is exposing more area within many fjords, which is increasing their potential for sequestration and making them rare negative (mitigating) feedback on climate change[17]. Fjords support rich cold-water coral reefs, and coral and sponge gardens that are biodiversity hotspots and significant sinks of organic carbon[18,19]. However, while sediment carbon accumulation and the biodiversity of fjord floors can be explored using dropped or towed gear from research vessels (e.g., Dunlop *et al.*)[20], a significant proportion of biodiversity and carbon storage occurs on their steep-sided walls. The exploration of these walls to assess their biodiversity and carbon stocks becomes difficult due to their inaccessible nature[21]. This is a considerable problem because fjord wall biota assessment is what might best be used to (1) prioritise designation of protection; (2) quantify fluxes and efficiency of carbon pathways from storage to sequestration; and (3) monitor changes in the performance of carbon storage in biota (e.g., growth) in response to diverse and interacting stressors.

For a holistic approach to surveying a species- and carbon-rich habitat and prioritising its protection, the difficulty of assessment of steep surfaces (a key piece of the jigsaw) becomes a weak link that needs to be solved. The problem of surveying biota on steep surfaces is not unique to fjords, but also occurs for marine cliffs, seamounts, volcanic island surrounds and coral reef drop-offs. It is typically tackled using Remote Operated Vehicles (ROVs) from research vessels or using Self Contained Underwater Breathing apparatus (SCUBA) in the shallows. However, both of these techniques are problematical for various reasons. Commercial and scientific SCUBA is very tightly regulated with minimum team sizes of highly qualified personnel that cannot travel far from 24-hour professionally run recompression chambers and is usually limited to working at less than 40 m depth for very short periods. Work-class ROVs are large, require engineer support and are similarly expensive and difficult to transport to remote areas, where most fjords occur. Once at the site, ROVs are much less limited in time underwater than divers, but analysing their video or still photographic images is hugely time-consuming because of the difficulty of quantifying errors in size and area. Even with lasers to give fixed dots on a plane, the areas photographed are usually at differing distances and angles, making later image analysis very time-consuming and hard to automate. However, uneven walls could also be challenging to operate manned submersibles at approximately fixed distances to seabed as well. A fixed focal length, down-looking camera dropped to the seabed on a tripod can photograph the same size area exactly perpendicular to the subject. With a precision flat port in its housing, middle range aperture (e.g., F11 on a camera aperture dial), good sensor array and appropriate lighting, such a setup can achieve better than 1 mm resolution and accuracy across the field of view - making biota identification, size and density estimation robust (see Barnes *et al.*)[22]. Such a system is accurate but requires a research ship and is difficult to use at slopes steeper than 45 degrees.

Technological developments are opening up some new possibilities for accessing and assessing remote fjords and steep surfaces. Here we consider and test two significantly different vehicle developments which pose potential solutions to this problem. These are mini-manned submersibles and autonomous underwater vehicles (AUVs). The former has existed for a hundred years and even AUVs have been widely used for open ocean physical oceanographic work for more than a decade. Changes in size and costs associated with these technologies have opened them up as powerful and non-invasive new tools in the toolbox for assessment of the seabed, life on it and its functionality, particularly with respect to biodiversity and blue carbon investigations. Here we consider two emerging marine technologies as tools to solve a particular problem - accurate biological mapping of steep surfaces in key environments like fjords, which in turn aids a wider issue of assessing carbon- and species-rich hotspots.

Mini-manned submersibles

ROVs and AUVs have steadily overtaken manned submersibles on scientific research ships and voyages, leaving manned submarines to be almost entirely for military use. Over the last decade, a new generation of much cheaper, single pilot, small, passenger submersibles has been built by companies such as Triton (US), U-boat worx (NL), Comex (FR), Silvercrest (UK), Seamagine (US) and others. Onboard seabed sonar helps to measure and correct the angle of camera to seabed. Such submersibles can be easily equipped with broadcast-quality camera systems, sensor arrays, robotic arms and other scientific tools. The range of possible auxiliary equipment is almost infinite as although the submersible manufacturers can supply them, most are aftermarket and can bolt on as "stand-alone" instruments. Subs are now being bought and operated by cruise and expedition vessels as well as private individuals, such that opportunistic science uses are emerging. Reductions in cost, size, maintenance and crew also make them attractive for science vessels.

However, the best opportunities for submersible science may lie in collaborative use of those run by tourism operations. Many operators actively encourage low or no-cost opportunistic use for science, but we encourage operators to make the most of emerging tools to engage in scientist-supported citizen science. IAATO (International Association of Antarctic Tour Operators) have now established guidelines on best practice for manned tourist submarine operations in the Southern Ocean. As they become more widely used, there will need to be proper assessments of their impact on nearby biota (e.g., potential disturbance of life on fjord walls). Piggy-backing on such voyages to use these platforms for scientist-supported citizen science gives an opportunity to reduce the need for logistically and carbon-expensive positioning costs of research vessels (getting a vessel to where you need to use it). Revisiting the same sites may represent both a bias as the most scenic places are likely to be chosen but also a big advantage; Using tourism voyages that visit the same sites year-on-year yields powerful opportunities for long-term monitoring. This is particularly important and useful given the very limited availability of such research vessels.

The wide observation field (compared with traditional scientific submarines), control of broadcast quality cameras with 330-degree rotation, coupled with sonars to give exact seabed distance and access to external sensor information, for example, sea temperature, give a scientific observer good potential for meaningful long term site monitoring protocols. Though cumbersome for small ROVs or AUVs, much of this equipment might also be possible to fit to work-class unmanned vehicles, but these are less readily accessible to science unless hired. To test the ability of such submersibles to investigate fjord walls and coastal sites, a U-Boat Worx Cruise sub 7 was fitted with two parallel lasers on board the vessel Seabourn Venture. Images were collected from Kulusuk in the East (site 1, Figure 1) to Nuuk in the West (site 6, Figure 1). A single 2022 voyage of fjord surveying [Figure 2] from Seabourn venture showed that it was possible on an unaltered, routine commercial voyage to obtain ~20 replicate images per site, with image resolution high enough for identification (by expert examination) to family/genus and assignment to morphological and functional groups [Table 1 and Figure 3], with quantitative area and to have corresponding, simultaneously collected environmental variables assigned to each [Table 1]. Latitude and longitude were assigned using USBL (Ultra Short Base Line) relay to surface to calculate real-time positioning. Depth was calculated using a combination of craft depth and distance/angle of onboard sonar. The latter was also used to estimate substratum profile (angle), while substratum type was observer assigned (on Wentworth scale). External (sea) temperature was directly measured using an onboard sensor (to which additional sensors could be added, e.g., for conductivity [salinity] or turbidity). Following image collection, additional augmental information can be added such as remotely sensed sea ice cover or primary production (*via* proxy of ocean colour, unshown). Image analysis (aided by software programmes or algorithms) can then be undertaken to gain morphotype and/or functional group presence [Figure 3]. Such data can then be directly compared across time (e.g., years, monitoring change) or space (habitats, environments or regions). It allows for the determination of change along polar basin troughs[23], emerging fjords[17], walls[24] or, when used in combination with physical collection of relevant local specimens and carbon content analyses of these, estimates of epibenthic carbon stocks[25].

Public engagement opportunities stretch beyond citizen science of image collection to demand for contextualizing education. Around Southern Ocean coasts and fjords, the environmental NGO Greenpeace is also finding that a small manned submersible can be a key tool to get expert assessments of vulnerable marine environments (VME) status and extent[24,26]. There are, of course, wider issues that need careful consideration, such as reputational management and national operator science programmes not being, or seen to be, dependent on tourism and private companies, amongst others. However, this philosophy has already worked for the monitoring of pelagic environments through, for example, the continuous plankton recorder survey[27]. With the increased urgency of identifying conservation priorities, avoiding critical

Table 1. Example synopsis of data from mini-submersible imagery along Greenland Fjords (from 2022). Columns are (left to right); site, sample size (images), geographic position and mean bathymetry, mean seasonal sea ice cover [Earth Observation from sentinel playground (https://apps.sentinel-hub.com/sentinel-playground/)], angle of substratum, sea temperature (in September 2022), dominant substratum type and roughness (× 10 mm). Morphotype richness and density are derived from data shown in Figure 3. The fjords are from Figure 1: Kulusuk (1); Skjoldungen (2); Aapilitaoq (3); Qaqatog (4); and Paamiut (5)

Fjord	*n*	Latitude	Longitude	Depth/m	Sea ice/days per yr	Substratum profile	Sea temperature	Substrate	Rugosity	Richness	Density
Kulusuk 1	8	65 37.471	37 12.049	33.4	59.3	26	1.36	Mud	2.5	2.9	4
Kulusuk 2	18	65 37.491	37 12.056	40.4	59.3	27	1.59	Mud	2.22	2.5	7.2
Kulusuk 3	19	65 37.52	37 12.05	30.8	59.3	17	1.88	Mud	2.26	2.4	5.8
Skjoldungen	17	63 31.031	41 44.512	115.8	86.7	83	0.02	Boulders	2.18	4.2	11.9
Aapilitaoq	20	60 09.89	44 16.789	96.5	10.7	84	0.56	Bedrock	2.81	7.5	33.3
Qaqatoq 1	20	60 42.6758	46 06.353	33.2	7.3	40	3.17	Boulders	3.35	4.4	29.2
Qaqatoq 2	20	60 42.6165	46 01.487	53.7	7.3	50	2.82	Boulders	3.25	5	26.8
Paamiut 1	10	61 58.809	49 41.305	34	8.7	32	3.89	Boulders	2.3	3.6	6.5
Paamiut 2	10	61 58.801	49 41.1880	33.2	8.7	35	3.8	Boulders	2.1	3.6	11.8
Paamiut 3	8	61 58.761	49 41.3434	60.4	8.7	53	3.8	Boulders	2	5	12.9

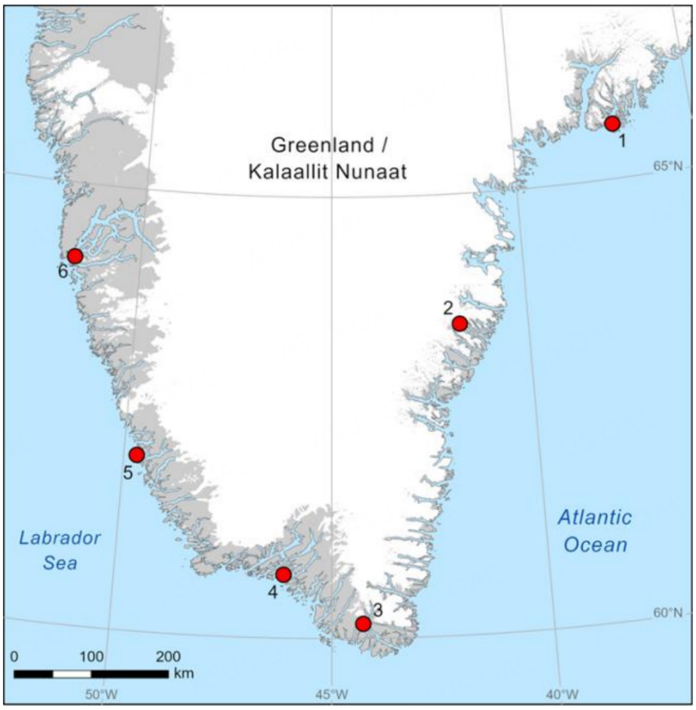

Figure 1. Fjord walls and seabed sites explored in 2022 using a Cruise sub 7 from an expedition ship. Science and conservation can make use of such opportunities for citizen science monitoring, engagement and education through repeat visits to key sites on voyages independent of science grants. The sites are Kulusuk (1); Skjoldungen (2); Aapilitaoq (3); Qaqatog (4); Paamiut (5); and Nuuk (6).

habitat degradation, good long-term monitoring and threat detection and management, it is important for science and scientists to be open to different and novel opportunities.

Figure 2. Launch and recovery from support vessels is aided by wireless remote control of submersibles (left). Manned submersibles can be used to non-invasively monitor key interface points in important habitats (such as the intersection of fjord walls with sediments, shown here on the right), non-indigenous species presence or other stressor responses.

Fjord	Polychaete annelids	Gymnolaemate bryozoan	Stenolaemate bryozoans	Barnacle crustaceans	Colonial ascidians	Solitary ascidians	Demospongiae, sponges	Erect gymnolaemates	Anomia bivalves	Articulate brachiopods	Crinoid echinoderms	Suspension feeding bivalves	Deposit feeding polychaetes	Bivalve molluscs	Gastropod mollusc	Regular echinoid echinoderm	Soft coral anthozoan cnidarians	Actinaria anthozoan cnidarian	Hydroid cnidarians	Octocorals	Errant polychaetes	Asteroid echinoderm	Pisces, Chordata	Spider crab, malacostraca crustacean	Generalist ophiuroids
Kulusuk 1	0.9	0.8			0.5		0.4	0.1						0.5					0.8		0.1				
Kulusuk 2	0.1	0.2			4.1		1.4	0.3					0.1	0.1				0.1	0.6			0.1	0.1		0.1
Kulusuk 3	0.1	0.2		0.1	1.9		1.3	0.3					0.3	0.1	0.1			0.1	1.3	0.1		0.1			
Skjoldungen	0.2	2.6	6.2	0	0.2		0.8	1.6							0.1										
Aapilatoq	0.2	1	0.3	0.2	0.9	0.2	6.8	1.8		0.2	0.3	15			0.1	0.5	0.1	0.4	3.4			0.1		0.1	3.8
Qaqatoq 1			2	1.3	0.6	0.7	4.6	0.1	20			0.1										0.2	0.1		
Qaqatoq 2	0.5	0.6		3.2	1.9	4.5	2.5	2.7	8.8						0.1		0.3	0.3	1.7			0.1			
Paamiut 1	0.6	0.5	0.6		0.7	0.2	1.3		1.8							0.2						0.6			
Paamiut 2	0.6	2	0.2	1.2		0.7	1.5		3.6									0.1	0.6			1.3			
Paamiut 3	0.1			0.9	1.3	1.1	2.4	2.3				0.4			0.1				4			0.4			

Figure 3. Taxonomic and functional group density in Greenland fjords (from image samples collected in 2022). Numbers are individuals per 0.5 × 0.5 m area. The functional groups are left to right; light grey [pioneer sessile suspension feeders], mid grey [climax sessile suspension feeders], dark grey [mobile suspension feeders], light yellow [unshelled deposit feeders], dark yellow [shelled deposit feeders], green [grazers], light pink [soft bodied, sessile predator/scavengers], mid pink [hard bodied, sessile predator/ scavengers], dark pink [soft bodied, mobile predator/scavengers], light red [hard bodied, mobile scavenger/ predators], dark red [arthropod scavenger/ predators], white [flexible strategy][23]. Geographic and environmental details of the sites are given in Table 1.

We recommend that the next steps for making use of manned submersibles on board expedition ships to aid science programmes are identifying where this can give added value to existing work (for example, recording biodiversity on fjord walls, where other research has gained corresponding data from basal sediments) or using images to ground truth and scale up to wider comparable habitats. Key to the success of such work will be the careful placement of the right equipment (e.g., laser arrays and lighting) and training to make sure the data gained is robust and does not come at the cost of environmental impact.

AUTONOMOUS UNDERWATER VEHICLES

AUVs are now being widely used for physical oceanographic data collection and seafloor mapping and range widely from powered vehicles, such as Autosub[28], to so-called "gliders" (e.g., Slocum by Teledyne and Seagliders by Kongsberg) that change buoyancy with an internal pump and angle themselves to glide shallower or deeper with internal weight movement. These can communicate at the surface using satellites to receive and transmit information, and thus can be at sea for months and travel considerable distances[28]. They offer not just cost-saving remote data collection, but multiple gliders can be deployed, enabling data collection from many places at one time, unlike a single research ship which can only be at one place at a time and often has other roles (e.g., polar logistics) to fulfil. Furthermore, small, manoeuvrable AUVs can access places un-navigable to a large vessel, such as parts of fjords beyond shallow sills, narrows or underneath ice shelves. Technological progress and scientific demand are steadily widening the uses that AUVs are being put to and problems being solved, such as upward-facing sensors to measure marine ice thickness over long under-ice distances[29]. It has proved more challenging to adapt AUVs to biological scientific work because of the high reliance on collecting and storing actual samples of organisms or the need for very precise locations (e.g., on the seabed). However, recently biologists are also now starting to make more and wider use of AUVs, such as in combination with Earth Observation (https://apps.sentinel-hub.com/sentinel-playground/) and surface craft, to profile ocean front-associated primary productivity and nutrient flux[30]. The large hovering style AUVs; "Autonomous Benthic Explorer" and "Sentry", work in steep terrain and in tandem with manned submersibles[31]. While these large AUVs have proved valuable at collecting biological data on seamounts and mid-Atlantic ridges[32], they require a dedicated research vessel for their operation and the associated costs are prohibitive to many research projects.

A new step in making AUVs a valuable biological tool has come with miniaturization, increased communication possibilities and adaptation of tools and programming to photogrammetry missions. Small, lightweight, portable AUVs can work together as a coordinated "swarm" on a programmed, joint mission with occasional communication to a shore- or small vessel-based pilot. The manufacturer PicSea makes a portable model, "3000" [Figure 4], of which we test deployed several, transported and supported just from the back of a small van, in a quarry in Scotland, UK in 2022. The test was to assess suitability for plans to potentially deploy a swarm to image benthic biodiversity along Scottish sea lochs and Norwegian fjords in 2023/24. The PicSea 3000 is one such type of AUV that can carry cameras to build composite, georeferenced and highly accurate imagery of the seabed using photogrammetry and image post-capture processing software. A number of such AUVs can be deployed to work together to give benefits of reduced cost, access to remote sites, and, importantly, low carbon footprint - as they do not need large vessel support or an adjacent research station. Small squadrons can be deployed from the back of a small land or sea vehicle and operated from a laptop computer. A new project (BluSwarm) has been proposed to use such AUVs to investigate the linkage between biodiversity and blue carbon on the steep sides of west Scottish sea lochs as proof of concept. It is probabe that field trials will involve considerable troubleshooting and innovation to develop both a robust protocol and sufficient accuracy, but then this technique can be applied in collaboration with other single AUV work to map biodiversity and marine spatial planning in northern Norwegian fjords - sites of mitigating feedback on climate change. Replicate image areas are collected for each site alongside physical variables (e.g., seabed profile, hardness and rugosity). Each organism is identified as far as possible, and the density of each taxon or functional group is then scored using image analysis. Reference data of biomass (drymass, ash-free drymass and carbon composition) at size for the relevant taxon/functional groups are then referred to, such that the densities of each biota can be converted into estimated carbon per organism type, per size[17,21-24,33]. Such data proves more powerful when combined with adjacent sediment core or grab collection, followed by the analysis of organic and inorganic carbon accumulation[34]. Several Norwegian mapping programs [MAREANO, Frisk Oslofjord (https://openarchive.ngu.no/ngu-xmlui/bitstream/handle/11250/2664214/2018_021.pdf?sequence=1&isAllowed=y) and Marine Coastal Basemaps] are now using single AUVs (Kongsberg, Hugin and Munin) equipped with acoustic and optical sensors to assess fjord biodiversity composition and abundance[35]. These AUVs are, however, most suitable for use on wide and flat areas on the fjord floor where data can be collected on bamboo and soft coral/sea pen forest habitats as well as coral mounds. Combining current and future

Figure 4. Launch and recovery of PicSea AUVs from a small boat, surface communications prior to diving, surveying sea loch biota on rocky substrates, and wreckage (clockwise from top left).

surveys with assessments of stored carbon stocks should prove important. Holistic value is then gained by surface monitoring of carbon capture (e.g., by remote sensing) and targeted sediment core collection and processing (to measure fate and sequestration of carbon). Therefore, fjord primary production is estimated using satellite-derived data, biodiversity variety and density by mini-submarines or AUV, and the fate of fjord carbon from biota measured from opportunistic cores, when possible. In turn, such biodiversity and organismal carbon stock assessments could then be used to inform conservation policy and protection designation.

There are, certainly, hardware and software challenges to overcome for AUVs to collect benthic biological data with the resolution and ease afforded by ROVs, which is why the latter still represent the mainstay of tools used to do this to date. Steep surfaces, such as fjord walls, are an ideal testing ground to develop the technology and find techniques of remote assessment that link biodiversity to blue carbon. However, close proximity to and contact with seabed poses a particular challenge for mini-submarines and AUVs due to risks of entanglement and becoming anchored. For AUVs, navigation, in particular, can be very tricky given some of the tight conditions and sills in fjords that might be unmapped or mapped at low resolution. Operations of either mini-submarines or AUVS at the sea surface are likely to be minimal at night, in bad weather or moderate wave chop/swell but dependent on the model type and site-specific hazards. There are also trade-offs to be considered in terms of vehicle type. Gliders typically provide longer duration, while those which are propeller driven have a wider ability in tasks and positioning. Obviously, as with most remote field science, expectation management and patience will be very important, especially because part of the point about linking such platforms with citizen science is encouragement and genuine involvement.

DISCUSSION

The last decade has seen a rapid increase in the growth and diversity of oceanographic vehicle fleets, capabilities and usage. Here we focus on specific applications (aiding biodiversity and organismal carbon assessments away from traditional blue carbon habitats) of just two types of vehicles in which rapid changes in technology are making them more scientifically available. The importance of mini-manned submersibles and coordinated AUV swarm vehicles and the exact position of scientific niches are likely to vary considerably with project, region and other co-users, for example, tourism. Internationally increased fuel costs, scientific vessel shortages and other factors (not least carbon footprint awareness) are only making scientific pragmatism, flexibility and leftfield thinking over tool use more and more important. The vehicles considered here are far from the only new technology solutions, with aerial drones particularly becoming more capable, cost-effective and used for science. In relation to example fjord ecosystems, these could be used to visualize the extent, geography and seasonality of sediment plumes coming from marine glacier termini at the innermost fjord ends. On the seabed, benthic crawlers have also developed considerably as tools for long duration, remote research[36] and applied research (e.g., seabed mining, Patania II). These can be combined with autonomous docking stations (Geomar's MANSIO & VIATOR) and used for not only Earth ocean floor missions but also planned exploration of other planetary and moon environments[37]. Other types of vehicles, such as ROVs, will remain important for many aspects of marine biological research and continue to be adapted to investigate niche scientific areas. These include research cold (lack of knowledge) spots, such as exploring iceberg scour impact on biota below SCUBA depths but in areas difficult for large vessels to access[38].

Vehicles are just one area in which technology is rapidly improving our ability to synergize approaches to tackling the crises of climate change and trying to halt nature loss. Remote sensing through improved Earth Observation access, resolution and techniques has made considerable leaps in improvement of monitoring the status and change at the top (https://www.wwf.org.uk/learn/walrus-from-space) and base[39] of food webs and carbon cascades. Similar success has been achieved using laser scanning of surfaces (LIDAR) on aircraft through, for example, collaboration between a commercial digital organization Hexagon with non-profit NGO Beneath the waves. This was used to advance the detection, mapping and analysis of Caribbean blue carbon habitats of seagrass meadows[40]. It is very likely that Artificial Intelligence/Machine learning (AI) will have increasing and diversifying applications, not least through automation of image analysis both at the identification of habitat and organism scale[41]. Likewise, the use of eDNA metabarcoding to sample environments for taxon presence has many potential advantages in terms of time, cost and invasiveness, not least in monitoring Marine Protected Area effectiveness[42] and the presence of vulnerable fjord ecosystems[43]. As with the cutting-edge vehicles considered here, AI and eDNA science is in their infancy when applied to seabed and marine carbon pathway investigations, but both clearly have considerable potential. Remote sensing, in contrast, has been used extensively in science but increases in resolution and application are opening it up to new avenues.

The example application we highlight is the ability of mini-submarines and AUVs to aid with biodiversity visualization and quantification in a species-and carbon-rich hotspot ecosystem, fjords. Although these tools could help science with some bottlenecks in field assessments, such as levels of biota density and (with calculations of mean carbon per individual per species) estimates of local carbon storage in macrobiota[17,22,23], other applications of new technology are also needed. On a larger scale, the potential for marine technology to help with carbon capture and storage (CCS) is recognized as huge and may be key in aiding the next step of removal from the carbon cycle to sequestration. Despite dominating our planet's area and living space, to date, most countries' planning of nationally determined contributions (NDCs) still has little role for the ocean in decarbonization. However, many emerging marine technologies that could change this are under consideration. Gattuso *et al.*[44] investigated the merits of four emerging, oceanic, negative emission technologies. They found no clear-cut ("decisive") measure to dramatically improve progress towards net zero (CO_2 emissions, under the Paris agreement). Most promise (and least side effect) was highlighted in schemes to increase coastal vegetation, whereas others were all still in "Concept Stage", such as marine bioenergy schemes (combined with CCS) and enhancing (1) open-ocean nutrient injection and (2) weathering. Evidence from various sources suggests species and carbon richness can overlap in hotspots[24,45], but many key blue carbon areas are unprotected[46] and under threat[9,10]. Alongside such massive and urgent research priorities, emergent ocean technologies of (and carried by) underwater vehicles may seem small. However, they may have important roles in research helping large schemes bear future fruit (e.g., protection) or tackling very specific problems, such as highlighted here, such as accurate mapping of steep surfaces in key biologically carbon accumulating environments like fjords[16,17,21]. Right now, they may be extremely helpful new tools in gathering key information to help prioritize, designate and implement meaningful marine conservation and restoration that truly helps tackle both climate change and nature loss while also lowering science cost and carbon footprint.

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Authors' contributions

Contribution to the conception and the development of the manuscript: Barnes DKA, Goodall-Copestake W, Weller K, Durrant A, Souster T, Dunlop K, Gossmann T, Sands CJ, Morley SA, Zwerschke N

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