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Editor's Choice

Arctic marine conservation is not prepared for the coming melt

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As the summer minimum in Arctic sea ice cover reduces in area year by year due to anthropogenic global climate change, so interest grows in the un-tapped oil, gas and fisheries resources that were previously concealed beneath. We show that existing marine protected areas in the Arctic Ocean offer little or no protection to many habitats and deep seafloor features that coincide spatially with areas likely to be of interest to industry. These habitats are globally unique, hosting Arctic species within pristine environments that are currently undergoing rapid adjustment to climate-induced changes in ocean dynamics, species migration and primary production. They are invaluable as reference points for conservation monitoring and assessment. The existing Arctic marine protected area network needs to be expanded in order to protect these habitats and be fully coordinated with other spatial and non-spatial measures intended to protect Arctic habitats and ensure any uses of Arctic marine or subsea resources are sustainable.

Keywords: benthic habitats, biodiversity, climate change, marine protected areas, sea ice.

Introduction

Arctic sea ice extent shows a steady decline from the date of accurate satellite monitoring (1979) to the present, from around 7.5 million km^2 in 1979 to around 4 million km^2 in 2016 (summer sea ice minimum, related to ice extent measured in September). The downward trend in Arctic sea ice cover over the last 37 years exhibits inter-annual variability but is unequivocal (Parkinson and DiGirolamo, 2016) and available evidence supports attributing the change to anthropogenic forcing (IPCC AR 5, Bathiany *et al.*, 2016; Song *et al.*, 2016). At the current rate of rising atmospheric CO_2 concentration, climate models predict that the Arctic will be ice-free in summer as early as 2030, although there is a wide (decade-scale) uncertainty in the model estimates (Jahn *et al.*, 2016).

Attendant with the changing climate and sea ice regime are changes in Arctic Ocean ecosystems. It is estimated that in a seasonally ice-free Arctic, the prolonged period of open-water conditions could result in a threefold increase in primary productivity (Arrigo *et al.*, 2008). Warmer ocean conditions coupled with changes in ocean circulation and ecological processes are already causing profound changes to the ranges and ecology of Arctic fish (Hollowed *et al.*, 2013a,b; Christiansen *et al.*, 2014), benthos (Kortsch *et al.*, 2012), birds and mammals (Wassmann *et al.*,2011; Descamps *et al.*, 2017).

In response to the decreasing sea ice conditions the question arises: Will industry move to expand operations in the Arctic to extract the newly accessible natural resources? This is a reasonable question to ask, given the world's growing demand for resources. The retreat of sea ice will make accessible, for the first time in human history, previously ice-covered fishing grounds, oil and gas deposits, and deep sea minerals, and will make possible new seaways to previously inaccessible coastlines and providing shorter and lock-free shipping routes between the Atlantic and Pacific.

Present and future Arctic industrial activity

Terrestrial mining operations are already well established in the Arctic for phosphate, bauxite, iron ore, copper, nickel and diamonds (Emmerson and Lahn, 2012). There are large mines operating in all Arctic countries and port facilities are used to export the product. New ports are planned, for example, at Iqaluit on

Canada's Baffin Island and Sabetta Port on the Yamal Peninsula, including the creation of a navigable access canal in the Gulf of Ob in Russia. Deep-sea mining has not yet started anywhere on earth (Baker and Beaudoin, 2013), but there are deep sea features in the Arctic (i.e. the Gakkel spreading ridge) that could become attractive to future mining operations (Michael *et al*., 2003).

The possibility of an Arctic shipping route that will give a 24% reduction in distance connecting the Atlantic with Pacific (e.g. for Shanghai–Rotterdam) compared with using the Suez Canal, is attracting the attention of the shipping industry. However, ships will still need to contend with harsher weather and (at present) floating sea ice, as annual winter freezing is predicted in all existing climate models. Regional year-round transport is operational today serving mines and oil and gas facilities. Arctic tourism brings over 6.5 million visitors each year with a steady upward annual trend of visitor numbers, tourist vessels and construction of facilities (Fay and Karlsdóttir, 2011). Although the (summer/fall season), cross-Arctic, cargo transport is presently minimal, one recent study (Hansen *et al*., 2016) has predicted that regular polar shipping using the Northern Sea Route (north of Russia) could be viable by 2040.

The Arctic contains vast oil and gas reserves and as the sea ice retreats, industry will inevitably seek to exploit the proven deposits (Figure 1). According to the US Geological Survey, the Arctic contains 13% of the world's undiscovered oil resources and 30% of its undiscovered conventional natural gas resources and these resources are mainly located (84%) in offshore sedimentary basins (Bird *et al*., 2008), primarily on the shallow shelves. Moves to exploit these offshore deposits are underway: the first offshore Arctic oil rig "Prirazlomnaya", operated by Russia's state gas monopoly Gazprom, started oil production in December 2013 in the Pechora Sea. Offshore oil and gas is extracted by the United States from the Northstar field in the Beaufort Sea and Norway started natural gas production from Snohvit in the Barents Sea in 2007 and oil production from the Goliath field in 2016.

Finally, there are valuable fisheries resources already being exploited in the Arctic ocean, and there are as yet unknown fisheries resources in the ice-covered region Arctic (Christiansen *et al*., 2014). A Working Group (2015) of Arctic fisheries experts concluded that there is a lack of information as to the species (fish and shellfish in particular) that may exist in the central Arctic Ocean and little is known of their geographic distribution. Northern migratory fish stocks are already migrating into the Arctic Ocean as the area of summer sea ice is reduced, but the extent to which this will occur is unknown (Hollowed *et al*., 2013a,b). Although at present there is optimism that an agreement on a moratorium on commercial fisheries in the Arctic can be negotiated (US Department of State, 2016), even if the negotiations are successful the moratorium will be time-limited. In the medium term, commercial fishing is interested to take advantage of the melting Arctic's newly opened waters to explore the region to develop new fisheries.

Conservation of Arctic marine biodiversity and habitats

Given the speed at which the Arctic environment is changing, it is prudent to review the level of protection that currently exists for Arctic marine biodiversity and habitats. In its 2015 Framework for a Pan-Arctic Network of marine protected areas (MPAs), the Arctic Council's working group on Protection of the Arctic Marine Environment (PAME) noted the need to "Identify types of important marine areas for protection at the pan-Arctic scale based on common criteria, goals, or objectives" (PAME, 2015). The Arctic Council's working group on Conservation of Arctic Flora and Fauna (CAFF) in its recent assessment of Arctic biodiversity has recommended Arctic countries to "Advance the protection of large areas of ecologically important marine, terrestrial and freshwater habitats, taking into account ecological resilience in a changing climate" (CAFF, 2013). In order for this action to be taken in the context of marine habitats, however, prerequisites are the identification and mapping of ecologically important areas. This is a challenge given the apparent lack of information on the geographic distribution of marine habitats.

Mapping of seabed geomorphic features offers a possible solution to this dilemma. Geomorphic features are fundamental attributes of the benthic environment that serve as a proxy for many benthic communities and ecological processes (Harris and Baker, 2012). Some well-known examples are seamounts (e.g. Clark *et al*., 2012), submarine canyons (e.g. Vetter *et al*., 2010) and hydrothermal vent communities living on mid-ocean spreading ridges (e.g. Tunnicliffe, 1992) but other categories of features including submarine plateaus, ridges and escarpments, also host various associated benthic communities (e.g. Harris and Baker, 2012). In other regions, maps of geomorphic features have proved useful for decision-making and marine spatial planning (Harris *et al*., 2008).

In this article, we examine the spatial distribution of seafloor geomorphic features in the Arctic Ocean in order to assess their current level of protection within existing MPAs. Our aim is to quantify the numbers and areas of different features occurring within and outside of MPAs as well as to identify the inventory of features that were once covered by year-round sea ice, but which are today exposed during the late summer, sea-ice minimum.

Methods

The study area is defined here as the average area of minimum sea ice cover in the 5-year period of 1979–1983 (7 449 000 km^2; Figure 1). Information on sea ice cover was collated from the National Snow and Ice Data Center, Sea Ice Index, Version 2 (Fetterer et al 2016). These data represent the extent of polar sea ice cover during September annually from 1979 to 2016 and have a spatial resolution (pixel size) of 25 × 25 km. The error of estimation for sea ice area is assumed to be one pixel or ± 625 km^2 (Fetterer *et al*., 2016), therefore areas relative to sea ice cover are rounded to the nearest 1000 km^2. Two time periods were chosen for this analysis, 1979–1983 and 2012–2016 (Figure 1). These two periods represented the earliest and latest data available on sea ice cover available in this data set. In order to account for annual variation, data across a 5-year window were used, with the sea ice extent for each period defined as areas where sea ice was present in at least 3 of the 5 years.

Seabed geomorphic features reported in this study were mapped by Harris *et al*. (2014) based on an interpretation of the Shuttle Radar Topography Mapping (SRTM30_PLUS) 30-arc second database (Becker *et al*., 2009), which incorporates the IBCAO 1-min compilation of Jakobsson *et al*. (2008) in the Arctic Ocean. Based on these data, Harris *et al*. (2014) mapped 29 categories of geomorphic features at a global scale to a spatial precision of ±10 km^2 (Harris *et al*., 2014). MPA boundaries were extracted from the IUCN and UNEP-WCMC database, which includes all MPAs regardless of their IUCN category (Category1a

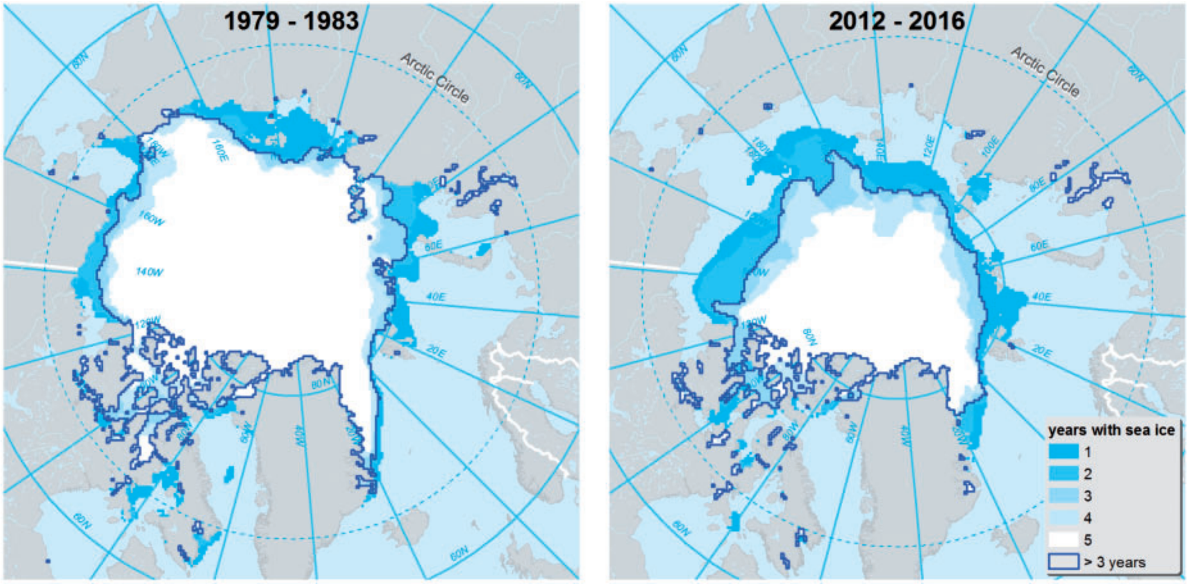

Figure 1. Sea ice extent for the periods 1979–1983 and 2012–2016 based on the National Snow and Ice Data Center, Sea Ice Index, Version 2 (Fetterer *et al.*, 2016). The mean area of sea ice cover in September has reduced from 7448,000 km^2 in 1981 to 4 624 000 km^2 in 2014, a difference of 2 824 000 km^2.

strict nature reserve; etc.). These data layers were loaded into ArcGIS to calculate the areas and numbers of different features within MPA's.

Results

Our analysis has identified the seafloor geomorphic features (habitats) that were formerly located below year-round sea ice but which are today located in open water during most (3 out of 5 years) summer sea ice minimum periods (Table 1). We have also identified the categories and areas of geomorphic features that are located within MPAs (Table 1). In the following section, we describe the areas of features that were located below year-round sea ice in 1979–1984 and that are now in open water during September. Next, we describe the features that are located within MPAs in terms of the areas formerly beneath sea ice but which are now in open water in September.

Features formerly located below year-round sea ice now in open water

An area of 2.8 million km^2 that was located below year-round sea ice in 1979–1984 is now in open water during September (Table 1). The seasonally open water area is 37.9% of the area that was formerly ice-covered year-round (Figure 2). An area of 1.9 million km^2 of continental shelf that was located below year-round sea ice in 1979–1984 is now in open water during September (Table 1), a change in area of 64.9%. For the continental slope, sea ice retreat has exposed 267 000 km^2, which is 48.8% of the area that was formerly ice-covered. For the abyssal zone, sea ice retreat has exposed 626 000 km^2, which is 16% of the area that was formerly ice-covered (Table 1; Figure 2).

The continental shelf has been subdivided into three roughness categories of low (<10 m), medium (10–50 m) and high (>50 m) vertical relief (Harris *et al.*, 2014). We found that 83.4% of formerly ice-covered low-relief shelf is now in open water during September, along with 58.3% of medium-relief shelf and 39.2% of high relief shelf. Superimposed on the continental shelf are valleys and glacial troughs. We found that 48.3% of formerly ice-covered shelf valleys are now in open water during September, along with 49.6% of glacial troughs and 32.8% of shelf-perched basins. In other words, of the area of shelf that is now open-water in September, it is the least rugose areas of shelf (low-relief shelf) that have experienced the greatest change in sea ice cover (83.4%); lesser amounts of change have occurred over the more rugose shelf areas (high-relief shelf plus glacial troughs and shelf valleys; Table 1).

Features that are associated with the continental slope include submarine terraces, canyons and escarpments. We found that 13.8% of formerly ice-covered terraces are now in open water during September, along with 37.3% of canyons and 15.6% of escarpments (Table 1; Figure 2).

The abyssal zone has been subdivided into three roughness categories: abyssal plains (<300 m relief), abyssal hills (300–1000 m relief) and abyssal mountains (>1000 m relief). We found that 23.1% of formerly ice-covered abyssal plains are now in open water during September, along with 12.1% of abyssal hills and 8.6% of abyssal mountains. Features associated with the abyssal zone include five categories of features that were formerly ice-covered but are now located in open water during September: basins, continental rise, troughs, fans, and plateaus. We found that 19.3% of formerly ice-covered abyssal basins are now in open water during September, along with 52.8% of the continental rise, 23.6% of submarine fans, 11% of troughs and 8.3% of plateaus (Table 1; Figure 2).

Finally, our analysis also identified three categories of seafloor geomorphic feature that have remained entirely beneath the sea ice zone year-round. These are: (i) ridges; (ii) the Gakkel spreading ridge (Jakobsson *et al.*, 2003); and (iii) its central rift valley (Table 1).

Features in MPAs formerly beneath sea ice now in open water

Only 2.33% of the areas located below year-round sea ice in 1979–1984 are located within MPAs. The existing MPA network

Table 1. List of geomorphic features occurring in the Arctic Ocean below the zone of minimum summer sea ice cover for the mean of 5-year periods 1979–1984 and 2012–2016.

Feature	Area km^2 beneath sea ice (1979–1984)	Area km^2 beneath sea ice (2012–2016)	Change in area km^2	Percentage of feature now exposed	Features within MPAs km^2	Percentage of features in MPAs	Area in MPAs now exposed km^2	Percentage of MPAs area now exposed
Shelf	2 965 000	1 042 000	1 923 000	64.9	170 210	4.0	117 350	68.9
Shelf—low	1 220 000	202 000	1 018 000	83.4	34 140	1.7	20 600	60.3
Shelf—medium	1 156 000	482 000	674 000	58.4	66 360	4.1	47 210	71.1
Shelf—high	589 000	358 000	231 000	39.2	69 780	8.4	49 530	71.0
Glacial trough	776 000	391 000	385 000	49.6	57 510	5.7	44 360	77.1
Shelf valley	855 000	442 000	413 000	48.2	61 680	7.2	46 550	75.5
Basins shelf-perched	321 000	216 000	105 000	32.8	21 750	4.8	15 320	70.4
Slope	570 000	295 000	275 000	48.4	3 500	0.3	1 710	48.9
Basins slope-perched	3 000	1 000	2 000	66.7				
Canyon	295 000	185 000	110 000	37.2	560	0.08	240	42.9
Terrace	134 000	115 000	19 000	13.8				
Trough	38 000	34 000	4 000	10.5	440	0.50	190	43.2
Escarpment	137 000	115 000	22 000	15.5				
Abyss	3 914 000	3 288 000	626 000	16.0				
Abyss—Mountains	758 000	693 000	65 000	8.57				
Abyss—Hills	1 532 000	1 346 000	186 000	12.1				
Abyss—Plains	1 624 000	1 249 000	375 000	23.1				
Abyssal Basins	2 171 000	1 753 000	418 000	19.3				
Plateau	773 000	709 000	64 000	8.29				
Ridge	73 000	73 000	0	0				
Rift Valley	17 000	17 000	0	0				
Spreading Ridge	147 000	147 000	0	0				
Total	7 449 000	4 624 000	2 824 000	37.9%	173 710	2.33%	119 060	68.5%

The table lists the difference in area between these two time periods, the percentage area of features now exposed in open water, the area of features within MPAs that were under sea ice in 1979–1984 and the areas of features in MPAs that are currently in open water. Geomorphic features in this study include three base layers (shelf, slope, abyss) over which all other features are superimposed, hence the sum of shelf, slope and abyss (light shaded text) yields the total area.

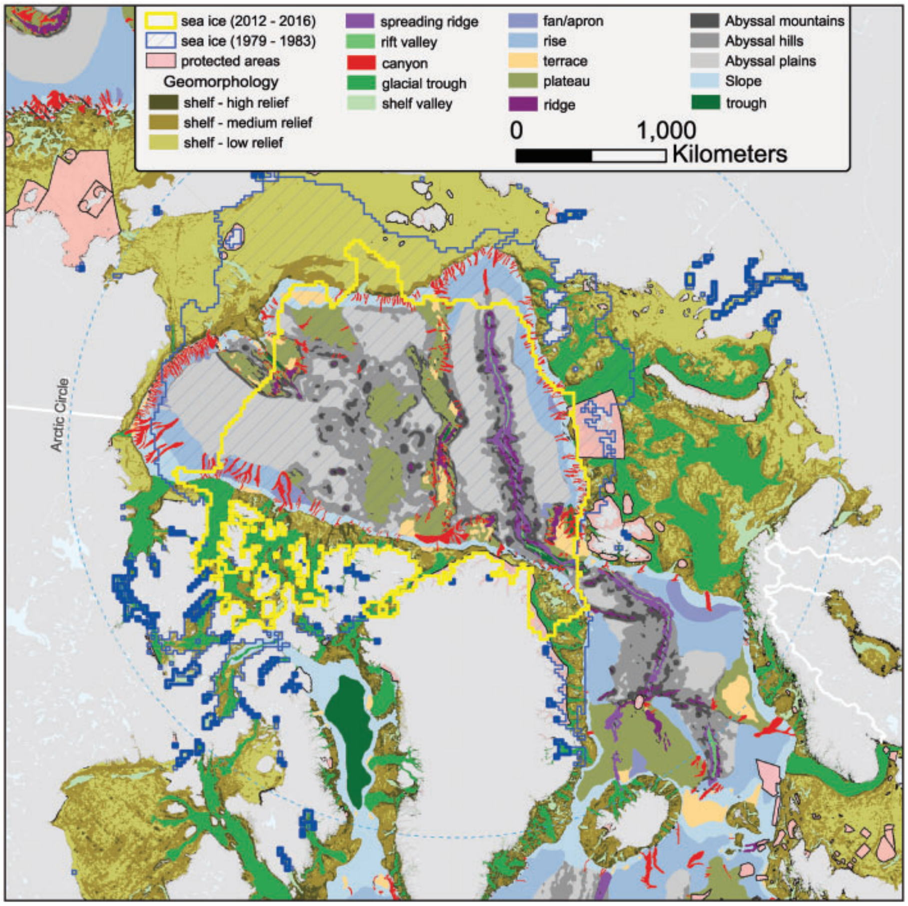

Figure 2. Geomorphic features map for the Arctic Ocean extracted from the global geomorphic features map of Harris *et al.*, (2014). Mean September sea ice minima periods of 1979–1984 and 2012–2016 are indictaed. The (diagonal line) shading indicates the (formerly) ice-covered area. Recently exposed areas of open water in September are located mainly off Siberia (Russian Federation) and Alaska (United States).

is focused on coastal and shelf habitats. Consequently, nearly all geomorphic features occurring inside MPAs are shelf features (Table 1). Of the 173 710 km^2 of area in MPAs, 170 210 km^2 (98%) is on the continental shelf. Some MPAs overhang onto the continental slope where the coastlines of Greenland, Svalbard and Franz Josef Land are close to the shelf break. Consequently, there are very small areas (3500 km^2) of slope features included in the existing MPA network (Figures 2 and 3; Table 1). There are zero abyssal geomorphic features within the existing MPA network.

The shelf features located within MPAs are low-, medium- and high-relief (seafloor roughness) classes, shelf valleys, glacial troughs and basins perched on the continental shelf. The total area of seafloor within MPAs is 173 000 km^2 which is about 4% of the shelf area that existed beneath sea ice cover in 1979–1984. The retreat of sea ice has resulted in 117 000 km^2 of shelf area within MPAs to now be occurring in open water during September, a change in area of 69% compared with sea ice cover year-round in 1979–1984.

The feature category with the greatest percentage area within MPAs is high-relief shelf, with 69 780 km^2 out of 589 000 km^2, or 8.4% of area in MPAs. Sea ice retreat has exposed 49 380 km^2 of high-relief shelf, a change of 63.8%. Interestingly, the area of low-relief shelf within MPAs exposed by sea ice retreat is relatively small (55.4%) compared with more rugose shelf types. This pattern is the opposite to that seen overall in the Arctic, in which low-relief shelf is the geomorphic category that has seen the greatest change (83.4%; Table 1).

Discussion

It is obvious that the existing MPA network in the Arctic Ocean is inadequate to protect the full range of habitats and biodiversity that occur there. The existing MPAs cover only 2.3% of the benchmark area used in this study (the area under year-round sea ice circa 1979–1984; Figure 3), which falls well short of the CBD Aichi target of 10%. On the other hand, Canada, the Kingdom of Denmark, the Kingdom of Norway, the Russian Federation and the United States, realizing the challenges of protecting and conserving deep sea Arctic environments, signed a “Declaration concerning the prevention of unregulated high seas fishing in the central Arctic Ocean” on 16 July 2015 (https://www.regjeringen.no/globalassets/departementene/ud/vedlegg/folkerett/declaration-on-arctic-fisheries-16-july-2015.pdf.) and a moratorium including Parties that are major participants in high-sea fisheries but not Arctic Coastal States is in late stages of negotiation (US Department of State, 2016). Hence the area beyond national jurisdiction in the central Arctic Ocean has some degree of protection from fishing pressure.

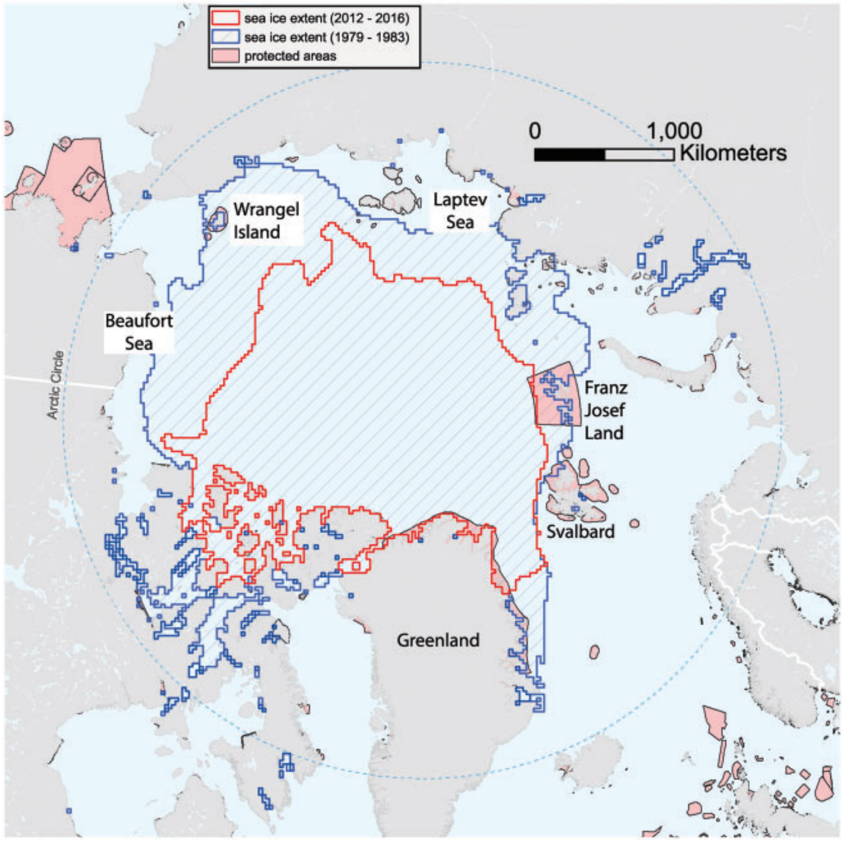

Figure 3. Location of MPAs in the Arctic Ocean in relation to the average extent of September sea ice minima periods of 1979–1984 and 2012–2016. MPAs in the areas around Wrangel Island, Franz Josef Land and Svalbard were previously within sea ice zones during 1979–1984 but have been in open water regions in September 2012–2016. MPAs along the coast of Greenland have remained within the year-round sea ice zone. The existing MPAs are a mixture of nature reserves and multi-use reserves. The Svalbard MPA is 74% nature reserve and 26% multi-use; the Franz Joseph Land MPA is IUCN category IV (multi-use); Greenland is IUCN category Ia (nature reserve) and Wrangel Island is also IUCN category Ia (nature reserve).

The existing MPAs are located mainly along coastlines and inner-shelf regions, and they do not cover any abyssal habitats and negligible protection is provided to slope habitats. But the seafloor is comprised of a complexity of different habitat types, which is represented at a coarse resolution by seafloor geomorphology (Figure 2). The existing Arctic MPA network is therefore not representative in the sense of MPA design (Rice and Houston, 2011). Here we discuss four categories of geomorphic features in greater detail to illustrate the complexity of existing benthic ecosystems and the different pressures that they face due to human activities.

It is acknowledged that full MPAs are not the only spatial policy instrument that can confer conservation benefits to biodiversity and promote sustainability of ocean uses. However, efforts to provide guidelines for application of the provision for the "other effective area-based conservation measures" consistently conclude that ensuring conservation effectiveness of "other" spatial measures requires site-specific knowledge of the nature and location of the biodiversity features requiring enhanced protection (Hockings *et al.*, 2006; Coad *et al.*, 2013; Jonas *et al.*, 2014), a conclusion acknowledged in conservation policy (CBD, 2016). With such knowledge of Arctic biodiversity in only early stages of acquisition, MPAs are the priority spatial conservation tool, until such time as there is lower uncertainty about these habitats (Grantham *et al.* 2009). The early recognition of critical ecological assets and the establishment of MPAs to protect them will avoid creating "residual reserves" (*sensu* Devillers *et al.*, 2014) after industries have become established.

Basins perched on the continental shelf

On the continental shelf, glacial erosion has created numerous basins that are natural traps for fine sediments and also for anthropogenic contaminants. At the time of the sea-ice minima of 1979–1983, an area of sea ice covered basins of around 321 000 km^2 occurred on the continental shelf, of which around 22 000 km^2 are located in MPAs (Table 1). Most glacial troughs have a raised rim at their seaward terminus, near the shelf break, forming basins perched on the continental shelf. Similarly, glacial erosion has incised smaller valleys, kettles, and other depressions which form basins. The broad shelves of the Barents Sea, the Siberian marginal seas, and the Chukchi Sea, exhibit abundant shelf-perched basins (Figure 4a).

Because basins act to trap sediment and associated particulate organic carbon (POC; Belicka *et al.*, 2002), they thereby trap most POC generated by shelf productivity or received from

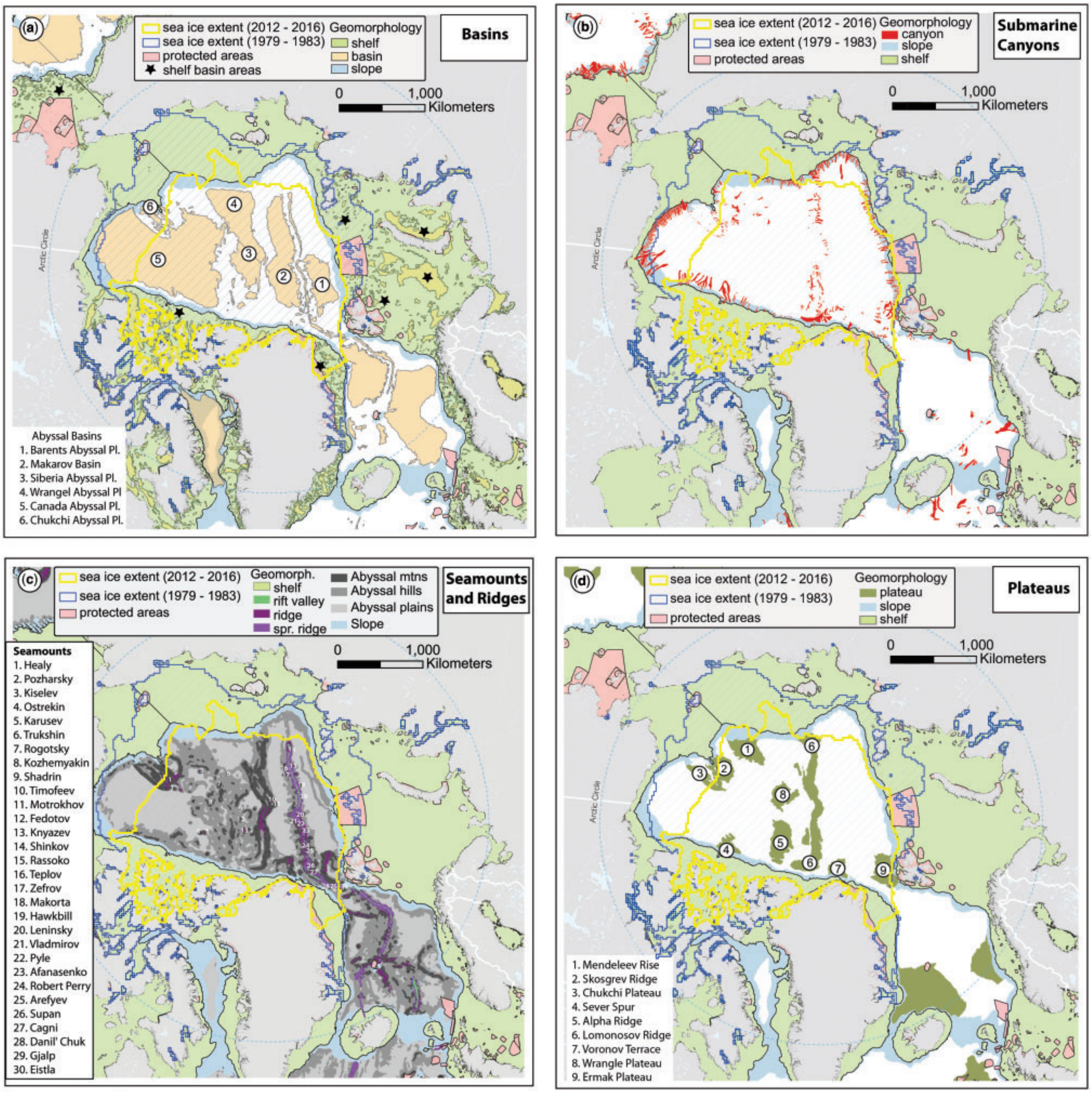

Figure 4. Maps showing specific feature types in relation to minimum (summer) sea ice extent: (a) shelf perched basins; (b) submarine canyons; (c) seamounts and deep sea ridges; and (d) submarine plateaus.

terrestrial runoff, which supports benthic infauna. Such basins would also trap any sediment-associated contaminants. In areas where shelf perched basins are common, the shelf exports very little sediment or organic matter to the deep Arctic Ocean environment (Piepenburg, 2005). Following this logic, the Barents Basin adjacent to the Barents Sea shelf, which is heavily covered with shelf-perched basins, might be expected to be receiving limited POC flux from the adjacent shelf. In contrast, the Canada Abyssal Plain (basin) might be expected to be receiving a greater relative POC flux from the narrow shelf along the Alaskan margin because there are very few shelf-perched basins in that region (Figure 4a).

Submarine canyons

On the continental slope, there are 337 submarine canyons occurring in the Arctic Ocean beneath the area of 1979–1983 sea ice minimum (Figure 4b). Canyons located within the 1979–1984 minimum sea ice zone cover an area of 295 000 km^2, but only small parts of three canyons, totalling 560 km^2 (0.2%) are currently protected in MPAs. Sea ice retreat has resulted in 103 canyons (37% of canyons by area) to now be in seasonally open water, which leaves them vulnerable to fishing and other anthropogenic pressures.

Interestingly, the newly exposed canyons are found mainly in the Beaufort Sea and the Laptev Sea (Figures 2 and 3). These regions are both characterized by a relatively narrow continental shelf which increases the likelihood that POC flux across the shelf and down-canyon thalwegs is an important ecological process in those regions (Piepenburg, 2005). The Beaufort Sea canyons could, therefore, be the most productive and biologically active canyon habitats in the Arctic Ocean.

Submarine canyons in other parts of the world are recognized as prime fishing grounds as well as biodiversity hotspots. They host cold-water coral communities and cetacean feeding grounds among other attributes (Brodeur, 2001; De Mol *et al*., 2010; Huvenne *et al*., 2012; Yoklavich and Greene, 2012). In particular, the largest, shelf-incising canyons are associated with oceanographic upwelling zones and enhanced productivity (Allen and Hickey, 2010; Harris and Whiteway, 2011).

Where it has occurred in other parts of the world, bottom trawl fishing has been shown to be particularly destructive to sensitive sea-floor habitats (FAO and UNEP, 2009), in some cases causing severe damage to benthic ecosystems (e.g. destruction of cold water coral habitat and sponge gardens; Norse and Crowder, 2005). Bottom trawl fishing has been shown to particularly impact the heads of large shelf incising canyons, ridges and the summits and flanks of seamounts (Althaus *et al*., 2009; Puig *et al*., 2012). Oil spill risk from operations on the continental shelf where that industry operates in other parts of the world (e.g. Brazil, Australia and West Africa) is relatively high for submarine canyons compared with other seafloor habitats because of the common correspondence between the occurrences of both canyons and prospective oil and gas areas (Fernandez-Arcaya *et al*., 2017).

Changes to ocean productivity and local currents, attendant with sea ice retreat, suggest that Arctic canyons are presently in a state of adjustment. Their ecosystems are likely to be in the process of adapting to the new, post-anthropogenic climate change environment (Wassmann *et al*., 2011).

An important point to consider is the near-pristine condition of these habitats. Most have never previously been exploited, which greatly enhances their value to science as benchmarks for future research. The study of species and ecosystems adapting to the new, post-anthropogenic climate change environment, is a further consideration to protect and conserve these habitats.

Seamounts and the Gakkel Ridge

The GEBCO Gazetteer (IHO-IOC, 2016) lists more than 30 named seamounts that occur in the area of year-round sea ice cover (Figure 4c). These seamounts lie mostly along the slow spreading Gakkel Ridge. The ridge and seamounts are both features potentially at risk from future human activities.

In other regions of the world, seamounts host highly biodiverse, fragile cold-water coral ecosystems, as well as valuable fisheries (Pitcher *et al*., 2007). The vast majority of seamount-associated demersal fisheries have proven to be unsustainable, undergoing a boom-and-bust cycle that has usually lasted <10 years (Koslow *et al*., 2015). Seamount flanks contain ferromanganese crusts comprised of cobalt, nickel, and rare earth elements used in high-tech industries and which may have commercial potential, although they are not presently being exploited (Hein *et al*., 2010).

The Gakkel Ridge is known to contain hydrothermal vent sites (Edmonds *et al*., 2003) and as such, it has a potential to be targeted for exploitation of its massive sulfide deposits. The whole of the Gakkel Ridge, with its central rift valley, lies beneath the present area of year-round ice cover (Figure 2). The best studied Arctic hydrothermal vents lie along the spreading ridge located between Iceland and Svalbard (Pedersen *et al*., 2010), which is within the zone of seasonally open sea ice.

Globally, interest in mining hydrothermal vent massive sulfide deposits is most advanced in the southwest Pacific, but there remain many unanswered questions regarding the environmental impact that mining will have (Boschen *et al*., 2013). Some scientists have questioned the wisdom of pursuing the mining of these poorly studied, highly complex and biodiverse, deep sea ecosystems (e.g. Van Dover, 2011; Van Dover *et al*., 2017).

Arctic Ocean plateaus

An interesting geomorphic aspect of the Arctic Ocean is the high percentage area of submarine plateaus that characterise the region. There are 773 000 km^2 of submarine plateaus in the Arctic Ocean, comprising 20% of the seafloor area beneath the 1979–1984 year-round sea ice zone (Table 1). These features are of mixed volcanic/continental origin and include Yermak plateau, Lomonosov ridge, Chukchi Plateau, Chukchi Rise, and Northwind ridge (Figure 4D). Some of these features have surfaces at a depth of around 1000 m which bear glaciogenic deep-sea bedforms (Polyak *et al*., 2001), probably formed during isotope stage 6 (Jakobsson *et al*., 2016).

Little is known about the benthic ecology of submarine plateaus, either in the Arctic or at a global scale. In the few studies that have been published on the ecology of submarine plateaus, biodiversity is thought to be increased in association with rocky habitats and in areas of increased geomorphic heterogeneity (Przeslawski *et al*., 2011; Sayago-Gil *et al*., 2012; Harris *et al*. 2011). In some cases, such as the Chatham Rise off New Zealand, plateaus support valuable fisheries, including bottom trawling which has impacted benthic habitats (Nodder *et al*., 2012).

In the Arctic, our analysis suggests that around 64 000 km^2 of plateau area, formerly beneath year-round ice cover, is now found in seasonally open water. This is mainly that part of the Chuckchi Plateau located adjacent to the Alaskan continental slope. The Chuckchi Plateau is also highly heterogeneous in a geomorphological context, which also has possible implications for its biodiversity (and hence conservation) values.

Biodiversity hotspots

As noted earlier, geomorphic features are fundamental attributes of the benthic environment that can serve as a proxy for many benthic communities and ecological processes (Harris and Baker, 2012). It follows that the diversity of benthic habitats can also be considered to be a proxy for benthic biodiversity and that the more heterogeneous the geomorphology of an area, the greater the potential the area has for increased biodiversity.The habitat heterogeneity hypothesis is a cornerstone of ecological theory (e.g. Tews *et al*., 2004).

In order to identify areas where the greatest geomorphic diversity occurs, a focal variety analysis was undertaken using ArcGIS (Esri, 2006). The focal variety tool counts the number of different categories (of geomorphic features in the present study) occurring within a specified search radius. We used a 1 km gridded raster of the geomorphic features map and specified a 100 × 100 grid cell (100 × 100 km) search area to produce a map of geomorphic heterogeneity (Figure 5).

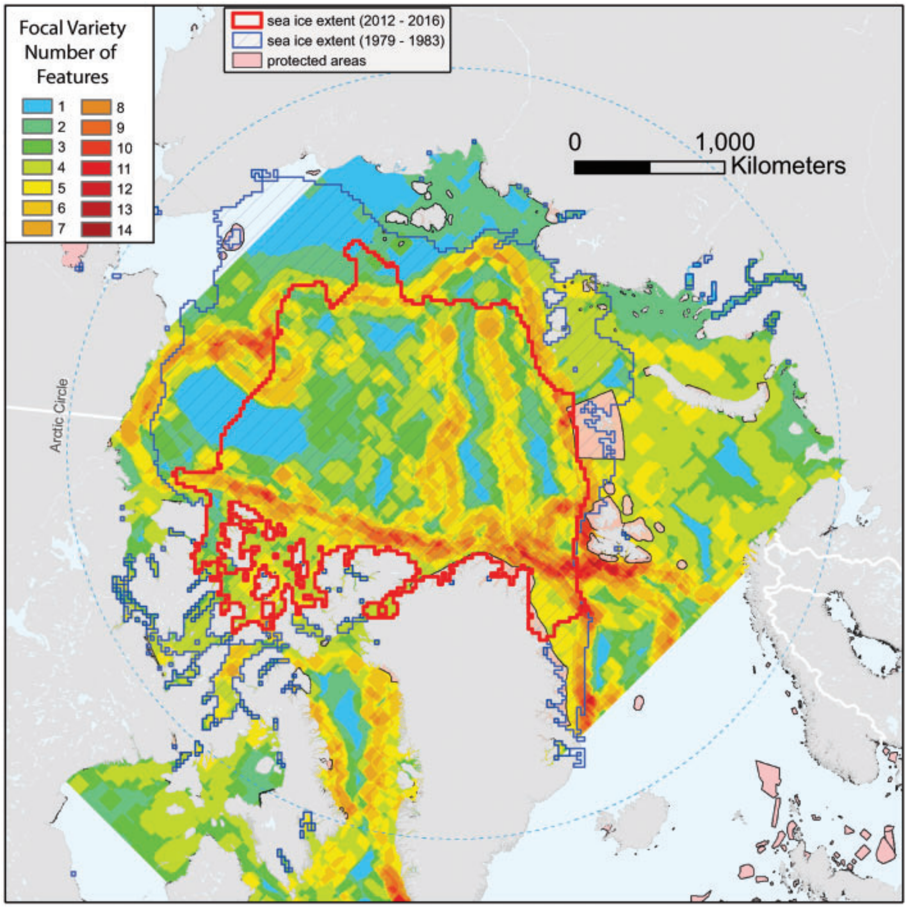

Figure 5. Map of seafloor geomorphic heterogeneity for the Arctic Ocean, produced using the focal variety tool in ArcGIS.

The hotspots of geomorphic heterogeneity (Figure 5) immediately suggest themselves as candidates for MPAs, where the maximum potential biodiversity can be conserved in the smallest possible area (Harris *et al.*, 2008). They are also areas where targeted marine surveys could be optimised to investigate the diversity of species and habitats. The Mendelev Rise and Chukchi Plateau region adjacent to the Bering Sea stand out as a potential hotspot, as well as the continental slope adjacent to Franz Joseph Land, Svalbard and at the shelf break across the Canadian archipelago (Figure 5).

Conclusions, recommendations, and future work

The retreat of the permanent sea ice zone over the past 30 years has resulted in the occurrence of seafloor geomorphic features in seasonally open waters for the first time in human history. These featutres include continental shelf, shelf valleys, glacial troughs, submarine canyons and submarine plateaus. They are likely in the midst of a rapid ecological transition as the Arctic ecosystems respond to global climate change. Prompt action is needed to put in place an interconnected, transboundary MPA network to conserve a representative set of these habitats and to achieve the Aichi target of 10% of seafloor area within MPAs by 2020. This would contribute to SDG14 in particular and help maintain regional peace through cooperation.

Future work to support the design of an an interconnected, transboundary, pan-Arctic MPA network should include expeditions to document baseline communities associated with different habitats and the integration of biophysical data in order to model potential biodiversity patterns. The existing geomorphic features map could provide a framework for the design of surveys of the Arctic benthic environment. Multivariate analysis of existing biophysical data has provided information at a global scale for benthic habitats (Harris and Whiteway, 2009) and efforts are underway to produce ecological marine units for the pelagic environment, also at a global spatial scale (Sayre *et al.*, 2017). These methods lend themselves to remote and inaccessible locations, where data are limited, such as the Arctic Ocean.

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