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Whole-ocean network design and implementation pathway for Arctic marine conservation

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Forestalling the decline of global biodiversity requires urgent and transformative action at all levels of government and society, particularly in the Arctic Ocean and adjacent seas where rapid changes are already underway. Amid growing scientific support and mounting pressure, the majority of nations have committed to the most ambitious conservation targets yet. However, without an approach that inclusively and equitably reconciles conservation and sustainable ocean use, these targets will likely go unmet. Here, we present ArcNet: a network design framework to help achieve ocean-scale, area-based marine conservation in the Arctic. The framework is centred around a suite of web-based tools and a ~ 5.9 million km² network of 83 priority areas for conservation designed through expert-driven systematic conservation planning using conservation targets for over 800 features representing Arctic biodiversity. The ArcNet framework is intended to help adapt to new and emerging information, foster collaboration, and identify tailored conservation measures within a global context at different levels of planning and implementation.

Urgent and transformative action is required at all levels of government and society in order to forestall the global decline of biodiversity^{1,2}. This need is particularly pressing in the Arctic Ocean and adjacent seas where unprecedented and cascading changes to ecosystems³ are risking the livelihood, health, and cultural identity of Indigenous Peoples and local communities^{4,5} as well as the physical and ecosystem services that are critical to Earth's life-support system⁶. The recognition that biodiversity loss is a main threat to global well-being and prosperity has been made at the highest levels^{6,7}, and amid growing scientific support and mounting pressure^{8,9}, the majority of nations have now committed to the most ambitious conservation targets yet¹⁰. However, without an approach that inclusively and equitably reconciles conservation and sustainable ocean use and includes an effective strategy for engagement and implementation, these targets will likely go unmet.

Networks of protected and conserved areas are central to international biodiversity conservation strategies^{8,11}. In this context, a network refers to a

set of ecologically representative and well-connected protected and specially managed areas that operate cooperatively to efficiently and effectively achieve conservation objectives and are integrated in the management of the wider seascape^{11,12}. Their contribution to effective, long-term conservation is well-established¹³, and expectations are that the global economy will benefit significantly from establishing far more protected areas than exist today⁹. Indeed, expanding but also effectively managing existing protected areas are central to safeguarding biodiversity and will contribute towards climate change adaptation and the preservation of ecosystem services^{3,6}: the natural infrastructure that supports human economic activity and wellbeing¹⁴. Nowhere is this more urgent than in the Arctic, where surface warming of at least twice¹⁵ and perhaps up to four times¹⁶ global average temperature is driving the Arctic region into a new ecological state with potentially alarming consequences¹⁷. Due to the unique and fragile biodiversity of the Arctic marine environment, its importance for Indigenous Peoples and local

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communities, and its role in moderating global climate, in 2015 the Arctic Council set out a common vision for a collaborative international response to establish a pan-Arctic marine protected area (MPA) network¹².

While momentum for internationally-agreed conservation targets has been building since the 1990s, progress has been underwhelming. The UN's Strategic Plan for Biodiversity 2011–2020, which called for 10% conservation of coastal and marine areas globally (Aichi Target 11)¹¹, was declared unmet after the 2020 deadline¹⁸. Perhaps motivated by: broad agreement that the 10% target was arbitrary and inadequate^{19,20}; strong scientific support for higher targets^{20–22}; and an observed shift in public concern for risks like biodiversity loss and climate inaction⁷, parties to the Convention on Biological Diversity have recently committed to the Kunming-Montreal Global Biodiversity Framework (GBF) targets, Target 3 of which aims, in part, to effectively conserve and manage at least 30% of global coastal and marine areas through ecologically representative and well-connected, area-based protected networks by 2030 (often referred to as 30 × 30)¹⁰. While such international targets are important for coordinating global conservation efforts²³, setting international standards, and drawing attention to environmental issues²⁴, their effectiveness in halting biodiversity loss has been the subject of some discussion²⁵. Indeed the GBF agreement is a remarkable achievement, but after decades of lagging behind deadlines, it is clear that enabling and motivating nations to commit to the timely implementation of the GBF targets remains the real challenge.

The literature has identified several key factors contributing to target implementation failures, which we interpret as barriers to effective conservation implementation generally. Firstly, it is widely accepted that there has been a long-standing gap between conservation research and its implementation²⁶ due in large part to a disconnect between researchers and practitioners²⁷. This disconnect is reflected in the paucity of broad societal participation in planning processes²⁸. While the importance of willing and able involvement of Indigenous Peoples and local communities at all stages cannot be overstated, there is also a need for more scientists to proactively engage in the setting of biodiversity targets as well as in the identification of assessment indicators for monitoring progress²³. To be effective, conservation targets, at all scales, need to be clear, unambiguous, scalable, and well-defined with explicit deliverables, which is not often the case²⁹. Indeed, we have observed a trend towards the implementation of opportunistic, ad hoc conservation initiatives that are not identified through formal network design, which risks their integration into the wider landscape and seascape. Finally, critical gaps in knowledge persist at the science-policy interface³⁰, particularly with respect to socio-ecological insights into feedbacks between institutional arrangements, governance mechanisms, and nature; their relationship with biodiversity conservation; and the incorporation of Indigenous knowledge and local knowledge (IK & LK) into biodiversity targets and network design³¹.

With these issues in mind, we propose a new approach targeting broad societal engagement, where people with rights, stakes, knowledge, and/or values linked to the Arctic Ocean (henceforth referred to collectively as stakeholders) unite to drive inclusive and equitable knowledge-based conservation design and implementation. Here we present ArcNet, an ecosystem-based network design framework whose aim is to help achieve ocean-scale area-based marine conservation in the Arctic in contribution to GBF commitments. ArcNet's network of priority areas for conservation (PACs; Fig. 1), which covers ~31% of the Arctic Ocean and adjacent seas, was identified using the decision support software Marxan with leading marine biodiversity experts and a spatial database of 818 systematically-selected conservation features (CFs) to represent Arctic biodiversity. ArcNet's PAC network and supporting framework, including the database, web-based tools, operational model for charting engagement and implementation, and growing community of practice, are now being rolled out to mobilize an unprecedented conservation initiative through pan-Arctic marine conservation design. An overview of ArcNet's adaptive, iterative framework is laid out in Fig. 2 and highlighted below with details in the Methods and SI sections.

Results and discussion

ArcNet network design for post-2020 Arctic conservation

In response to the need for urgent action in the face of rapid changes in the Arctic Ocean and surrounding seas, WWF initiated the pre-emptive design of a whole-ocean conservation network that is rooted in the best-available scientific data of Arctic biodiversity. Here, we differentiate between “planning”, which concerns the implementation of established principles and procedures to solve a preconceived problem, and “design”, which we consider the conceptualization of a framework to address a problem independently of any such a priori constraints. ArcNet's network is based on such a design approach to systematic conservation planning (SCP): an iterative, multi-component, multi-stage analysis that is widely valued as best-practice for its transparency, defensibility, flexibility in the face of competing interests, and ability to achieve both ecological and socioeconomic conservation goals with limited resources^{28,32}. The Arctic Council's vision is for such a pan-Arctic network to contribute to ecosystem-based management (EBM) of the region's Large Marine Ecosystem (LME) management units^{12,33}, where humans and their activities are recognized and managed as an integral part of the ecosystem. While design proposals for such networks have been made in the Russian³⁴ and Canadian³⁵ Arctic and some progress has been made in Greenland³⁶, no whole-ocean network has ever been designed in the Arctic or elsewhere. Therefore, ArcNet's intention is to help provide this network for the circumpolar region while facilitating and enhancing the implementation of EBM by linking ocean-scale ecosystem-based network design to EBM at the level of individual Arctic LMEs.

Several key innovations were required to overcome the challenges of undertaking SCP on this scale. At ArcNet's foundation is a set of agreed conservation criteria and principles (see *Aims, objectives, and project governance* in “Methods”) as well as a database of best-available spatial data representing ocean-scale Arctic marine and coastal biodiversity. A key principle to highlight is that economic and financial considerations were excluded from the analysis in order to provide a scientific framework to underpin discussions with stakeholders going forward where considerations of societal and economic values would play a more central role. After identifying a list of prerequisite CFs using internationally-agreed criteria (Table S1), the database was built through an ambitious data mining and quality control exercise. In the data-heterogeneous and often data-sparse Arctic (see *Data deficiency* in Supplementary Information, SI), the teams searching for data to represent each CF had to be mindful of data availability and quality issues. Thus, a set of clear guidelines was formulated to guide data mining, which is outlined in the Methods section (see *Data mining*). The resulting 818 spatial data layers (Table S2 for the full list) were selected to capture important features of biodiversity that are special, critical, rare, unusual, or unique (distinctive features) and examples of regionally typical habitats and diversity (representative features). Setting conservation targets for each CF in the network was undertaken systematically through an expert-driven, criteria-based scoring system for distinctive features that was uniquely linked to a proportional assignment approach for the representative features according to each CF's spatial extent. This approach ensured that, rather than being policy- or politically-driven, the network's conservation targets were instead rooted in the conservation needs of each CF. Details of ArcNet's CF selection and target setting exercises are provided in SI.

The SCP analysis itself was undertaken using Marxan; a widely-used conservation planning and decision support tool that provides alternative optimised solutions to predefined conservation objectives and targets through iterative analysis cycles and expert elicitation³⁷. ArcNet's Marxan analysis and its innovations are described in full in the Marxan analysis sections of the Methods and SI. The final cycle of this process yielded solutions that efficiently satisfied ArcNet's conservation objectives and targets, and, after review by internal and external experts and several tailored adjustments, the final set of ArcNet PACs was confirmed (Fig. 1), resulting in the ~5.9 million km² network of 83 PACs. Details of each PAC are provided in Table S3 with close-up views of the PACs in the European, North American, and Eurasian sectors provided in Fig. 3. Summary



Fig. 1 | The ArcNet domain and PAC network. The ArcNet domain was defined by the southern border of the 18 PAME-defined regions of the Arctic Ocean and adjacent seas, known as the Arctic Large Marine Ecosystems (LMEs)³³, and focussed on the Arctic realm as defined by the Marine Ecoregions of the World⁵⁸, with some

modifications (see *Project scope and defining parameters* in SI). The network of 83 PACs was designed to include existing marine protected areas (PAs, as shown in figure), but the migration bottlenecks were determined separately and were not included in the Marxan analysis (see *Post-Marxan analyses* in SI).

statistics of their areal distribution across national exclusive economic zones (EEZs), the Central Arctic Ocean area beyond national jurisdiction, and the Arctic realm as defined by the Arctic Council’s Conservation of Arctic Flora and Fauna working group (CAFF) are given in Table 1 along with a comparison to existing protected areas.

Uniquely in ArcNet’s SCP analysis, ecological coherence was achieved at the ocean scale by strategically selecting CFs to represent spatiotemporal variability and redundancy over the Arctic region. Also, several post-Marxan analyses have been completed to address key issues that could not be wholly addressed within ArcNet’s Marxan analysis. These include investigations into: the seasonality of CFs in each PAC, conservation in a changing climate, capturing connectivity, and migration bottlenecks (see *Post-Marxan analyses*). Importantly, the network’s 31% coverage of the study area was based on a Marxan solution to ArcNet’s predefined criteria and thus was determined independently of and prior to the GBF 30% target¹⁰. Implementing this network, therefore, as a stand-alone protected area network would satisfy, for the Arctic region, the ecologically representative and well-connected requirements of the GBF’s ambitious Target 3. However, the intention is for the ArcNet framework to

guide network design at finer scales, driven by inclusive engagement, charting a pathway to implementation for an Arctic marine conservation network.

Guiding inclusive engagement, network design, and implementation

Since much of Arctic marine conservation is implemented at the national and sub-national scale, ArcNet was designed to support these finer scale conservation efforts with an operational model to guide broad, inclusive engagement at all stages of network design and implementation on a foundation of best-available data and a transparent SCP analysis. This support is delivered under the consistent terms of reference of ArcNet’s conservation criteria and principles via three key components: the growing community of practice; the web-based tools that provide participants with access to ArcNet’s PAC network and database; and a platform for organizing and facilitating inclusive engagement, charting a pathway to implementation. These components of ArcNet are discussed below.

Since inception, ArcNet has brought together many experts from academia, government, and non-governmental organizations (NGOs)

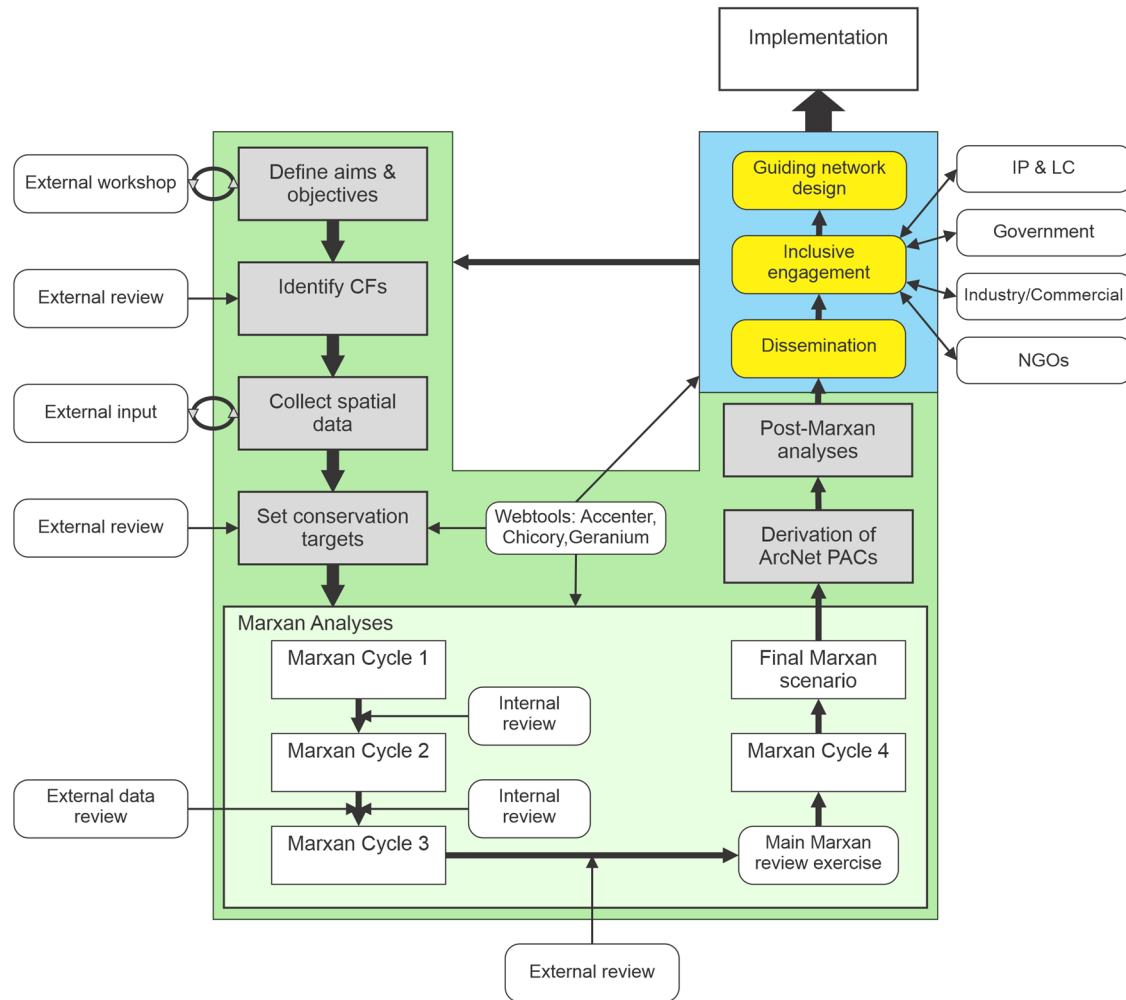


Fig. 2 | Overview of the ArcNet framework showing the two main project phases with key steps and the adaptive iterative design process. Shaded areas encompass ArcNet activities with green and blue areas indicating those of the analysis and implementation phases, respectively, and the latter showing (in yellow) the steps currently underway on ArcNet’s pathway to implementation. The arrow cycling back to the early stages of the analysis represents the integration of new and emerging

information from both new data sources and conservation partners as they join the ongoing design process. Thus, broad engagement will ensure the inclusion of emerging actor-owned knowledge as well as value-determined CFs (e.g., ecosystem services and resources), which were not included in the initial design of ArcNet’s PAC network, in any pan-Arctic conservation network. CF conservation features, IP & LC Indigenous Peoples and local communities, NGO non-governmental organizations.

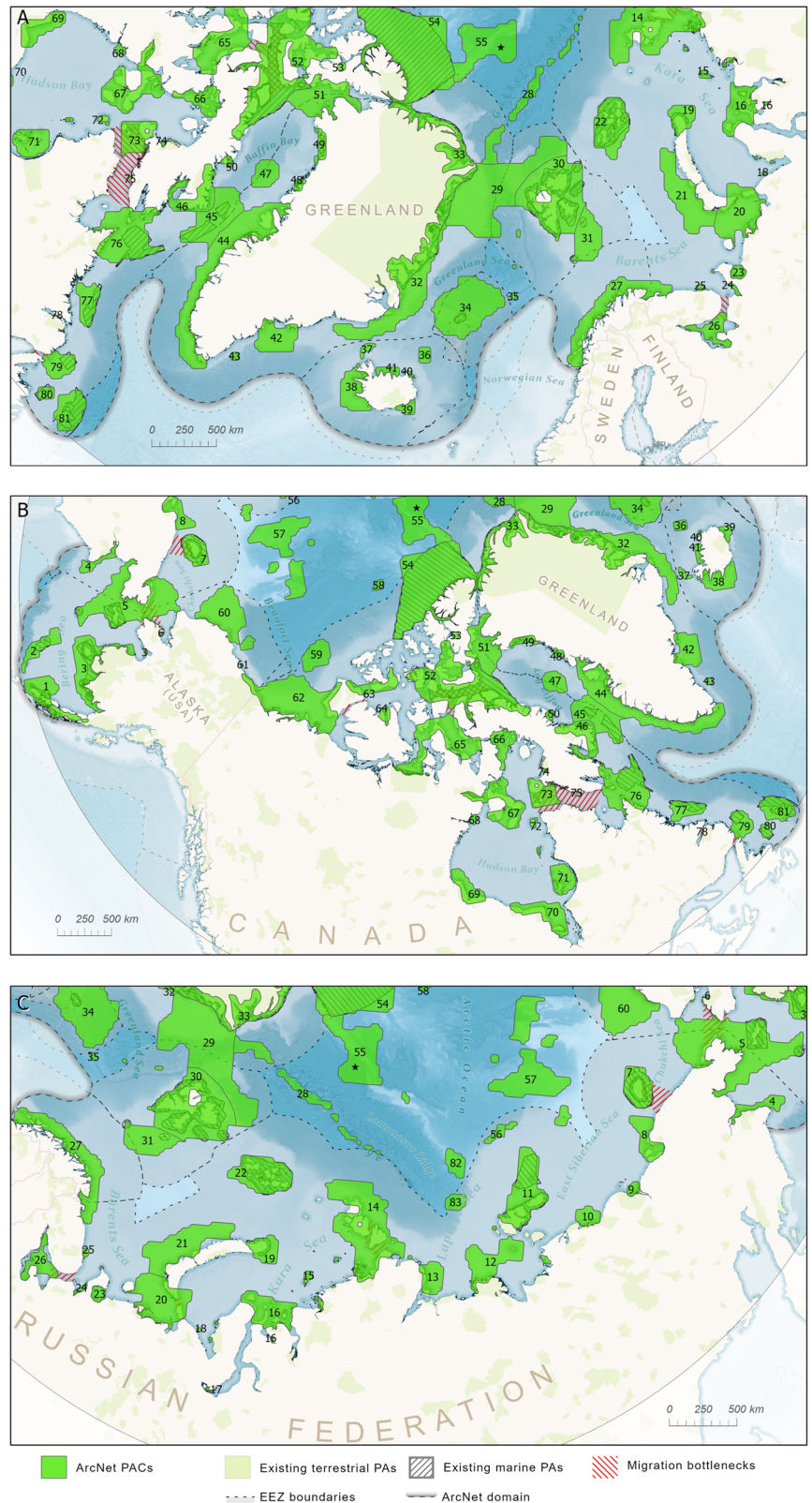
though its review and data mining activities. This community of ArcNet contributors has formed the scientific foundation of ArcNet’s community of practice. Through ongoing engagement with IK & LK holders, rightsholders, institutions from the local to international levels, and other marine stakeholders, this community continues to grow and will be able to provide local, regional, and international Arctic conservation initiatives with unprecedented expertise and momentum during planning, implementation, and management phases.

A transformative development for the support of conservation initiatives is ArcNet’s innovative suite of integrated web-based tools that provide transparency and instant access to key Marxan results, the PAC network, and underlying database with basic query and analysis functionality. First, CHICORY³⁸ is a portal for exploring the CFs and analysis results that underpin each of the 83 PACs (Fig. S1). Users can select a PAC via its ID number or clickable map, upon which its oceanographic setting is provided along with a report giving the PAC’s metadata, including its CFs, contribution to targets, thematic group diversity as well as basic statistical information (Fig. S2). From here, links are provided to reports for each CF that give a map of the CFs’ spatial data, metadata, including description and source, and a list of the PACs where it is found (Fig. S3). Next, ACCENTER³⁹ is a web-based GIS of the ArcNet database and PACs for executing simple queries, analyses, data extraction, and overlays (Fig. S4). It is a powerful tool

for providing conservation participants with interactive and instant access to the full depth of the ArcNet database and Marxan output. During the design process, these tools play a key role in facilitating discussions between participants and identifying appropriate conservation measures. By providing transparency, they also help ensure that the data and analyses behind conservation actions will be understood by those who will be directly affected⁴⁰.

Critically, ArcNet’s ocean-scale design framework includes an operational model that explicitly addresses the long-standing gap between conservation research and its implementation²⁶, thereby helping ArcNet transition from an academic exercise towards real conservation action. This pathway to implementation takes the form of coordinated and targeted activities to: disseminate ArcNet’s vision and PAC network to encourage broad participation and recruit innovative partners; engage inclusively with stakeholders to help empower them within a transparent process and identify their common visions and shared values; guide network design at finer scales; and develop steps to secure implementation at all levels (see Fig. 2). To this end, ArcNet takes advantage of WWF’s expertise in fostering broad societal engagement and in developing and delivering innovative solutions. Now, these discussions, which hitherto have occurred independently and under varying terms of reference, can occur under a consistent framework that is informed by the same high-quality resources. To facilitate, ArcNet has

Fig. 3 | The ArcNet PAC network by sector with EEZ boundaries⁵⁹. A European sector. B North American sector. C Eurasian sector. PACs are labelled with ID number that correspond to the list in Table S3. North pole is marked with a black star.



developed GERANIUM⁴¹, an engagement and visualisation tool for ecosystem-based marine spatial planning and tailored area-based conservation. The tool provides a visualisation of local and feature-specific needs to help prioritize engagement, organizes and guides discussion, and fosters cooperative processes across marine stakeholders, thereby helping to tailor conservation measures for each locale (Fig. S5 and S6). Importantly,

GERANIUM's innovation goes beyond conservation planning and network design. Rather, it provides a tool to set the PAC network in the context of the greater seascape (e.g., LME, marine ecoregions of the world, EEZ, etc...), linking ecosystem-based network design to marine spatial planning. This will enable the identification of effective conservation needs in the GBF's protected 30% (according to Target 3), but also actions to support and enhance

Table 1 | ArcNet PACs in the context of exclusive economic zones (EEZ) and CAFF boundaries

Region	ArcNet domain (AD)			CAFF boundary			Existing protected areas (PA ^a)			
	Region area within AD (x 10 ⁶ km ²)	PAC area within region (x 10 ⁶ km ²)	PAC area as % of region	Region area within CAFF (x 10 ⁶ km ²)	PACs area within CAFF (x 10 ⁶ km ²)	PAC area as % of EEZ in CAFF	Existing PA area within AD (x 10 ⁶ km ²)	% of EEZs within AD covered by existing PA	Existing PA area within CAFF (x 10 ⁶ km ²)	% of EEZ within CAFF covered by existing PAs
Canada EEZ	3.961	1.611	40.7	3.898	1.512	38.8	0.557	14.059	0.536	13.744
Central Arctic Area BNJ	2.806	0.406	14.5	2.806	0.406	14.5	0.000	0.000	0.000	0.000
Greenland EEZ	1.795	0.799	44.5	1.733	0.736	42.5	0.078	4.347	0.078	4.503
Iceland EEZ	0.42	0.092	21.9	0.39	0.071	18.2	0.003	0.654	0.003	0.772
Norway EEZ (inc. Svalbard and Jan Mayen)	1.171	0.592	50.6	1.637	0.592	36.2	0.080	6.824	0.081	4.94
Norway EEZ (mainland)	0.293	0.098	33.4	0.549	0.098	17.9	0.001	0.354	0.002	0.363
Jan Mayen EEZ	0.172	0.155	90.1	0.293	0.155	52.9	0.004	2.441	0.004	1.433
Svalbard /Spitsbergen EEZ	0.706	0.339	48.0	0.795	0.339	42.6	0.075	10.577	0.075	9.393
Russia EEZ	4.516	1.104	24.4	5.007	1.104	22.1	0.165	3.658	0.200	3.991
United States EEZ (Alaska)	1.279	0.484	37.8	2.218	0.484	21.8	0.089	7.032	0.422	19.041
Total AD (inc. land)	22.367	5.868	26.2	-	-	-	-	-	-	-
Total AD (marine)	16.392	5.087	31.0	-	-	-	0.972	5.929	-	-
Total AD within EEZs	13.088	4.682	35.8	-	-	-	0.972	7.426	-	-
CAFF area	-	-	-	32.365	5.647	17.5	-	-	-	-
CAFF area (marine)	-	-	-	18.314	4.876	26.6	-	-	1.320	7.207
CAFF area within EEZ	-	-	-	14.824	4.499	30.4	-	-	1.320	8.903

Note the significant difference in coverage between existing protected areas (EPA) and that required to achieve the conservation targets set out in ArcNet.

^aProtected areas, marine part only (see Fig. 1).

conservation in the remaining 70% through, for example, renewable resource management and safeguarding connectivity.

The ArcNet framework, its tools, and operational model have been developed with a number of key end users in mind, including Indigenous organizations, the Arctic Council, and the state departments mandated to establish marine protected areas. We anticipate Indigenous organizations to use the ArcNet scenarios and individual CFs to inform planning for individual sites or conservation networks while contributing IK to ArcNet engagement activities. While we hope the Arctic Council will use the framework to guide member states and promote MPA network development at the pan-Arctic scale, states themselves can use ArcNet scenarios for the development of a network plan if one is not already in place or for providing previously-identified national networks with a pan-Arctic context. Similarly, we expect ArcNet to lend support to a number of international marine conservation efforts. For example, ArcNet represents an opportunity to help governments of Arctic coastal states fulfil their international obligations under the GBF. However, ArcNet's network also includes several PACs that lie in-whole or in-part in marine areas that are beyond national jurisdiction, primarily in the 2.8 million km² Central Arctic Ocean. Until recently, no process existed for establishing and governing marine protected and conserved areas in these sectors of the Earth's oceans. However, the new and historic UN High Seas Treaty (HST)⁴² will soon provide a novel mechanism for establishing conservation measures in these previously out of reach areas. Here, state actors or groups thereof, in consultation with regional bodies, will be able to submit proposals for area-based management tools to the HST, informally facilitating collaboration. The HST will become a critical assist for the implementation of Target 3 of the GBF, with ArcNet contributing to proposals for protection in the Arctic waters.

Importantly, the Central Arctic Ocean is also the focus of the International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean (Central Arctic Ocean Fisheries Agreement, CAOFA). This agreement between Arctic and non-Arctic signatory states with Arctic fishing stakes aims to safeguard healthy marine ecosystems and secure the conservation and sustainable use of fish stocks against unregulated fishing through the application of a long-term strategy of precautionary conservation and management measures, including a 16-year moratorium (from June 2021) on commercial fishing. During this period, only exploratory fishing will be permitted while conservation and management strategies are under discussion. Although establishing fishing sector-specific area-based conservation measures are not currently under discussion, doing so does fall within the remit of the agreement, and the ArcNet framework is well-positioned to contribute to these discussions. Similarly, ArcNet will be able to inform opportunities through the International Maritime Organization (IMO) to establish shipping-sector specific area-based tools in the Arctic Ocean (including ABNJ) that would protect pelagic and sympagic CFs from the impacts of shipping.

Finally, while ArcNet purposefully did not include economic features in the identification of the PAC network, these considerations are ultimately critical because of the close association between environmental protection and conservation and economic production and prosperity; a linkage that is recognized by the High Level Panel on a Sustainable Ocean Economy (HLPSE)³. Economic considerations for protection put forward by HLPSE may provide opportunities for establishing and managing areas within the PAC network, thereby contributing to the area-based conservation component of marine spatial planning that has been identified as a key element of the HLPSE-promoted Sustainable Ocean Plans⁴³.

We assert that ArcNet's approach can overcome previous barriers to achieving conservation goals by: functionally integrating conservation design with the knowledge, visions, and values of all conservation participants; helping to promote ownership of conservation action for Indigenous Peoples, local communities, and other stakeholders; and helping to identify and activate the national and regional processes that can translate conservation initiatives into real conservation action. Further details of ArcNet's ongoing and proposed engagement and implementation activities are provided in the Methods section (see *ArcNet's pathway to implementation*).

Supporting conservation in the longer term

As progress is made towards a whole-ocean Arctic marine conservation network, ArcNet's role will evolve to one of long-term support, with several important contributions. First, while a conservation network based on the ArcNet PACs will, by design, support biodiversity resilience and persistence in the face of rapid changes driven by climate and human activities (see *Capturing dynamic elements* in SI), ensuring that conservation objectives continue to be met into the future will require an adaptive and iterative approach to management. Here, uncertain or highly variable systems can be monitored, and management strategies can be adapted accordingly to observed or anticipated changes^{44,45}. At the global level, monitoring (and subsequent assessment) was identified as a key support mechanism of the 2011–2020 Strategic Plan for Biodiversity, and its role has been reinforced in the GBF^{10,46}. As effective monitoring will require a set of change indicators that are tailored to conservation objectives²³, ArcNet's PAC network can equally be treated as priority areas for monitoring, using selected CFs from the spatial database as indicators on which the network and management objectives can be adjusted.

Although increasing monitoring capacity will require considerable investment since substantial improvements in monitoring capabilities are required¹, empowering knowledge-, rights- and other stake-holders with ownership of conservation action will enable, in many cases, effective monitoring and stewardship (and enforcement) to be undertaken locally⁴⁷. Also, as monitoring and adaptive management will be heavily dependent on both new and emerging data, an accessible spatial and temporal data repository and sharing platform will be crucial. Currently, the absence of such an open data sharing platform and data accessibility in general has been identified as a major hurdle in Arctic science⁴⁸. As data availability and access have significant effects on management decisions, such a resource is especially important for the data-sparse Arctic. Such a platform would go beyond linking to existing raw data collections, like the Global Biodiversity Information Facility, the Ocean Biodiversity Information System, and the linked Arctic data catalogues, by curating broader information related to CFs, like management-relevant metadata, derived data products, seasonal spatial and temporal detail, conservation status, etc. This would provide an active, collaborative, and systematically organised pan-Arctic data platform, purpose-built for biodiversity conservation and management applications. We believe that ArcNet's ocean-scale database and web interface is a ready-made starting point for such a repository and a model for ocean-scale data sharing elsewhere. With a suitable host and caretaker to foster a culture of data co-ownership, most of the barriers to data sharing could be overcome¹. Based on its mandate to address the conservation of Arctic biodiversity and promote practices which ensure the sustainability of the Arctic's living resources, we believe that CAFF is well-positioned to take ownership of this initiative.

While ArcNet will contribute towards achieving the GBF's Target 3 for the Arctic and surrounding seas, its design framework can equally act as a blueprint for whole-ocean conservation networks elsewhere and ultimately make important progress towards establishing a global ocean conservation area network⁴⁹. With the HST agreement now in place—a vital step for achieving the GBF's targets for marine areas—the reality of establishing a global marine conservation network is within reach. However, it is important to note that even such a network can only be effective in reversing the decline of nature if unsustainable practices in the remaining 70% are addressed by acting on the direct and indirect drivers of biodiversity loss and environmental degradation. ArcNet supports marine spatial planning and EBM across all of the Arctic Ocean and its adjacent seas by complementing and contributing to their implementation with an ocean scale context. This level of transformative change is going to require an unprecedented level of international cooperation, and we believe this can begin with ArcNet.

An invitation to join the ArcNet community

So far, internationally-agreed conservation targets have failed to embolden governments and society to act aggressively to forestall the global decline of biodiversity, and now the current geopolitical situation with the Russian

Table 2 | Asks of key conservation participants

Arctic governments	To cooperate with rights-holders, stakeholders, scientists, Indigenous knowledge and local knowledge holders, Arctic communities, marine managers, and industries in international processes to: <ul style="list-style-type: none"> • create national and ecoregional marine networks of protected and conserved areas that integrate the ArcNet PACs and apply an ArcNet-style systematic and participatory approach to conservation; and • establish effective conservation measures for identified priority areas.
The Arctic Council	To support ArcNet’s ocean-scale dimension by: <ul style="list-style-type: none"> • developing and sustaining programmes across its working groups to help establish the emerging Arctic Ocean network of conserved and protected areas and monitor and assess its conservation effectiveness; and • facilitating collaborative government processes to establish conservation measures for identified priority areas that are situated fully or partly in Arctic Ocean Areas Beyond National Jurisdiction.
People living in the Arctic (with rights, stakes and/or values linked to the Arctic Ocean)	To participate in and co-design conservation planning and processes to ensure conservation features and measures for identified priority areas reflect societal values, including Indigenous values.
Indigenous knowledge and local knowledge holders	To develop or lead co-designing processes and tools that incorporate Indigenous and local perspectives and knowledge in conservation objectives and planning, network design, monitoring programs, and effective conservation measures.
Marine managers and conservation professionals	To engage in collaborative processes to identify, develop, establish, and assess the effectiveness of conservation measures for the identified priority areas and to advise on their integration with ecosystem-based planning and management of the surrounding seascapes.
Marine scientists	To contribute to refining, establishing, and adjusting ArcNet’s PAC network by: <ul style="list-style-type: none"> • refining its knowledge base through monitoring, compiling, assessing, and reporting best-available spatial and status information of Arctic marine biodiversity; and • engaging in sub-national, national, and international marine protected and conserved area networks processes using an ArcNet-style systematic approach and integrating ArcNet’s ocean-scale results.
Marine industries	To acknowledge identified priority areas and support effective conservation by: <ul style="list-style-type: none"> • participating in multi-stakeholder processes at sub-national, national, and international levels to establish conservation measures for identified priority areas; and • contributing to the development and establishment of industry-specific guidelines, standards and legal instruments that contribute to effective conservation for identified priority areas and the surrounding seascape and comply with them.

Taking unprecedented action to implement a conservation network in the Arctic region will require all conservation participants to fulfil their obligations, and in support, WWF will continue to convene or facilitate cooperative processes to implement ArcNet.

Federation has dealt a serious blow to the continuation and expansion of broad collaboration on environmental issues in the Arctic. We must hope that its effects will only delay, not annihilate the agenda to establish national- and international-level ecosystem-based marine conservation of biodiversity in the circumpolar Arctic. After all, Russia has continued to engage in relevant international processes such as the CBD, the HST, and the CAOFA. Additionally, the Arctic Council, under the current Norwegian chairship, is still able to proceed with parts of its agenda where Arctic and Arctic-relevant exchanges remain active albeit in diminished capacity.

While the IPCC has found that governance across administrative boundaries and sectors tends to be too fragmented to provide an integrated response to the threats facing the ocean³, ArcNet has been designed to help bring together conservation partners from across society with governing institutions under a single framework. Under this framework, conservation partners can unite to overcome previous barriers to implementation and reconcile effective conservation with other interests, ultimately contributing to a sustainably-managed Arctic Ocean. Taking ArcNet from an academic exercise to an implemented pan-Arctic conservation network is a shared responsibility across all levels of government and society, and thus, ArcNet is calling on conservation participants across the globe to get involved with the ArcNet community. Specifically, we are targeting key players with specific asks in mind, including: the Arctic Governments; the Arctic Council; IK & LK holders; marine managers and conservation professionals; marine scientists; marine industries, and people living in the Arctic (Table 2). Together with the agreement for the conservation and sustainable use of marine areas beyond national jurisdiction nearly in place⁴², marine conservation at the ocean scale and beyond is within reach, and the first step is to successfully achieve a whole-ocean marine conservation network across the Arctic.

Methods

Motivated by both the slow progress towards global biodiversity targets and the Arctic Council’s 2015 framework for a pan-Arctic marine protected

areas (MPA) network, in 2017 WWF launched ArcNet, an initiative to develop a whole-ocean network design framework for Arctic marine conservation as a blueprint for international conservation efforts. The project has involved dozens of experts and reviewers, hundreds of data contributors, and representatives from all 5 coastal Arctic nations over its lifetime. The analysis phase, which is the main focus of this section, has now given way to the implementation phase where the ArcNet framework, armed with WWF’s expertise in multi-stakeholder engagement, will bring together, guide, and inspire stakeholders in Arctic marine conservation towards achieving the GBF Target 3 goal of 30% conservation by 2030 (30 × 30)¹⁰. Here, we present a summary of the ArcNet analyses (with full details provided in SI with specific subsections referenced in parentheses) and an overview of ArcNet’s pathway to implementation going forward.

Aims, objectives, and project governance

The ArcNet initiative has two central aims:

1. to identify an ecologically representative and well-connected Arctic network of priority areas for conservation (PACs) using a systematic conservation planning approach that will support the resilience and long-term conservation of biodiversity and ecological processes across the Arctic marine environment (analysis phase); and
2. to ensure that the resources and outputs from the analysis are used to help design, implement, and manage a conservation network in the Arctic Ocean (implementation phase).

The objectives of the analysis phase then are to:

- undertake a methodical, repeatable, and transparent systematic network planning, using Marxan, with well-defined ecological objectives and the best-available data (completed);
- define a PAC network, based on this design exercise, and make the database and Marxan results available via a set of web-based tools to inform ecosystem-based planning, facilitate engagement, and support

the implementation of an Arctic network of marine conservation across the wider seascape (completed); and

- strengthen the network by addressing additional conservation concerns such as connectivity and pressures from human uses and a changing climate (ongoing).

The objectives of the implementation phase (all ongoing) are to:

- initiate and engage a community of practice for open, inclusive marine conservation design throughout the Arctic;
- invite the international community to join ArcNet and be a part of an unprecedented collaboration to make ArcNet a conservation reality; and
- disseminate the ArcNet vision and facilitate stakeholder engagement in marine conservation efforts at all levels.

The governance of ArcNet (see Fig. S7 and more details in SI) was designed to be expert-driven through specialist thematic teams (i.e., marine mammals, sea birds, fish, sea-ice habitats, benthos, and coastal features) and a scientific analysis team, with external expert elicitation at several stages, all overseen by a steering committee consisting of WWF senior management with representation from all Arctic coastal states and the Arctic Programme. With this support, the steering committee made all final decisions, including, for example, geographic and temporal scope of the study, spatial resolution, and key definitions (see *Project scope and other defining parameters*), while a project management team (PMT) was responsible for day-to-day operations.

Defining ArcNet's conservation features: overview

Conservation features (CFs) are the measurable and spatially-defined components of biodiversity that are to be conserved within a planning network⁵⁰. In the context of ArcNet's long-term conservation of Arctic marine biodiversity, they represent the important biological, ecological, and socio-ecological elements of the Arctic marine ecosystem that the analysis aims to protect. The selection of CFs was guided by a carefully formulated set of objectives and criteria. Compiling a list of CFs for each thematic team was the responsibility of the thematic leads and their teams with guidance from the scientific analysis team, steering committee, and invited experts. A summary of this critical process is provided below with additional details in SI (see *Defining ArcNet's conservation features*).

Objectives and criteria, and additional design considerations. The objectives and criteria for CF selection in ArcNet were derived from internationally-accepted standards for identifying important areas for conservation (i.e., the CBD's Ecologically and Biologically Significant Areas, EBAs; IUCN's Marine Protected Areas, MPAs; and IMO's Particularly Sensitive Sea Areas, PSSAs, summarized from ref. 51 in Table 1 of ref. 12) and include: uniqueness or rarity; special importance for life history stages of species; importance for threatened, endangered or declining species and/or habitats; vulnerability, fragility, sensitivity, or slow recovery; biological productivity; biological diversity; representation of biogeographic "type(s)"; and ecological integrity (supporting ecosystem structure and function). Additionally, we added a refugia criterion to support habitat stability or species persistence by including locally unique combinations of physical characteristics like climate variables, oceanography, and topography⁵². We also added a socio-cultural and socio-ecological criterion to include species and/or populations (and their key habitats) of special importance for coastal communities. Importantly, aside from this criterion, a decision was made early in ArcNet not to include any value-determined features (e.g., ecosystem services and resources) as CFs, but rather to focus the analyses in the first instance on the needs of biodiversity. Economic and social considerations were reserved for post-analysis discussions where key actors in future adaptive iterations of the analysis can substantiate such value-determined features.

CFs were selected to capture two key objectives: (1) any geophysical and/or biological features that are special, critical, rare, unusual, or unique

and are of particular importance for biodiversity (distinctive features); and (2) examples of typical habitats and diversity within a region (representative features). These objectives were informed by a set of criteria that were drawn from four ecological categories: (i) species (populations) and their habitats; (ii) communities and their biotopes; (iii) biogeocenoses and seascapes; and (iv) ecosystem functions and the areas representing them. ArcNet's objectives and criteria for defining CFs are provided with examples in Table S1.

The ArcNet CF selection process was also guided by the reserve design considerations of Lötter et al.⁵³ and the Arctic Council's PAME MPA Network Toolbox¹³. More specifically, with details in SI (see *ArcNet network design considerations*), additional design considerations addressed by ArcNet include: introduced and non-Arctic species; capturing dynamic elements; bridging land and sea; connectivity; data-deficiency; and several considerations, summarized in PAME (2017)¹³, that address protecting refugia, persistent multi-year ice zones, replication, and high C sequestration sites.

Data mining. The ArcNet analysis was based on existing data that were sourced via an ambitious and systematic data mining exercise. Populating the identified CFs with data also followed the internationally-accepted criteria for identifying important areas for conservation, i.e., CBD EBAs, IUCN MPA, and IMO PSSA (see above). Note that ArcNet was not involved in the collection of any field data. Rather, guided by the scientific analysis team with detailed instructions for data collection, templates, and examples of data layers, the thematic teams were responsible for seeking out existing spatial data layers and metadata for the identified CFs. The a priori identification of ArcNet's CFs ensured that their selection was based on established objectives and criteria for conservation rather than on data availability. When appropriate data were unavailable, modelled data was preferred, and failing that, surrogate data were used when supported by the literature. In a few cases, raw unpublished field data was used when deemed appropriate by the thematic leads and reviewers. Data sources and methodological notes are provided for all CFs in Table S2.

Data sources for each CF and their metadata were submitted by the thematic teams to the scientific analysis team to be catalogued, standardized (e.g., reprojection to the North Pole Lambert Azimuthal Equal Area projection and conversion to ESRI shapefile format), and quality controlled. All data management and processing was fully documented. A rigorous quality check of each dataset ensured that any detected errors could be flagged, corrected, and documented for expert review (see below). Details on data processing and software are provided in SI (see *Data processing and software*).

Finalization of ArcNet's CFs and database. Towards the end of the data mining exercise, the thematic leads, scientific analysis team, project management team, and a number of invited experts met to review the CFs and data collected thus far. CF lists and data were adjusted in response to feedback, and the thematic leads followed-up with written reports summarizing the CFs chosen for their thematic group and any justification. These reports, the list of CFs, and all data were further reviewed by independent experts who provided final feedback on any omissions. Following this last round of feedback, the final list of ArcNet's 818 CFs (Table S2) and their associated spatial dataset were ready for use in Marxan. The distribution of data layers across the ArcNet domain and other summary information of ArcNet's final list of CFs are provided in Fig. S8.

Setting ArcNet's conservation targets

In a Marxan analysis, each CF is given a target for its conservation that reflects the objectives of the proposed network⁵⁰. These conservation targets determine the proportion of each CF's spatial extent that will be included in the final network design. While CF selection determines what to protect, target setting determines how much to protect. For example, a target of 30% for a beluga feeding habitat CF would result in at least 30% of these areas being included in any resulting network. Ideally, target setting for ArcNet would be based on robust knowledge of species and ecosystems. However,

since this information is often unavailable, especially in the data-sparse Arctic, a more pragmatic approach is required. In ArcNet, a number of key innovations were required for target setting due to the ocean scale of the analysis and the large number of CFs that resulted. Briefly, target-setting in ArcNet was a systematic process where targets were calculated for distinctive and representative CFs separately, using a criteria scoring system for the former (Table S4) and proportional assignment that was linked to the distinctive targets for the latter based on each CF's areal coverage. However, some CF targets were individually tailored in order to address specific conservation objectives that were raised by the thematic teams and external experts. Importantly, this systematic and tailored target setting exercise was followed by an internal and external review of each CF in order to ensure the final targets, which were used to generate the ArcNet PAC network, were result-based and tailored to the ArcNet objectives. Details of the full ArcNet target setting exercise is provided in SI (see *Setting ArcNet's conservation targets*).

Marxan analysis

Overview. Marxan is a conservation decision support tool⁵⁴ that was developed for conservation efforts at the Great Barrier Reef⁵⁵ and since has become the most widely used conservation support software³⁸. It is designed to be used iteratively with a series of calibration and exploratory analyses and several opportunities for expert feedback, providing planners and stakeholders with the information required to make transparent, rigorous, and science-based conservation decisions. Broadly speaking in ArcNet, four Marxan cycles were undertaken, using version 2.4.4.C⁵⁶ of the software. After each cycle, the results were reviewed, and the results and lessons learned were incorporated into the next cycle. The first two cycles were used for calibration of the technical parameters as well as testing of the initial set of conservation features and targets (see *Technical calibration and exploratory scenarios*). The third cycle included the full dataset following adjustments made after external review. Its focus was for scrutinizing the results using different conservation target levels in preparation for the main review exercises where internal and external participants followed an innovative process to rigorously assess the results thus far (see *Preliminary full Marxan analysis and review exercise*). This feedback was imperative for shaping the fourth and final cycle, which formed the foundation of the ArcNet PAC network (Fig. 1; Final Marxan cycle and derivation of the ArcNet PAC Network). A list of the main Marxan scenarios that were undertaken and their parameters is provided in Table S5. While a detailed account of all four cycles of the Marxan analyses is provided in SI, as the precursor to the ArcNet PAC network, the fourth Marxan cycle is summarized below.

Fourth Marxan cycle and finalization of the ArcNet PAC network. The fourth Marxan cycle was the culmination of the results of the previous 3 cycles and post-analysis reviews. This final cycle consisted of a series of scenarios to identify a configuration of PACs that fulfilled all criteria and satisfied all contributing experts, ultimately providing the final scenario on which the ArcNet PAC network was based. Once this final scenario was completed, a number of additional scenarios were run to highlight different aspects of that final network going forward, e.g., the effects of including/excluding existing protected areas, distinctive CFs only, and exploring any seasonality. Ultimately, Marxan scenario 4_4_1 in Table S5 formed the foundation of the final PAC network and, therefore, we discuss this scenario's output further here followed by the subsequent steps that were taken to arrive at the ArcNet PAC network of Fig. 1.

While Ardron et al.³⁷ provides a full account of Marxan analyses and the interpretation of results, for the purposes of this discussion, we provide a brief overview here. A Marxan "scenario" is an optimized selection process where the specific conditions and inputs of the scenario, such as its CFs, their conservation targets, and any parameter settings, are met for the least "cost" (i.e., total area in ArcNet; see *Project scope and other defining parameters*). This is accomplished with a simulated annealing algorithm that evaluates many alternative combinations of selected areas (called "runs") to identify a

"best solution" according to the score of an objective function. Thus, this best solution is a map that gives a set of planning units (PUs; see *Spatial resolution in Project scope and other defining parameters*) that together efficiently meet the CF targets that were set for the scenario. A complement to the best solution map is the "selection frequency" map that shows how many times each PU was selected in all the runs of that scenario. Therefore, a higher selection frequency provides an indication of PUs that are considered irreplaceable in the analysis and thus were included most often as part of the best solution. Together, these two maps are a good overall summary of the scenario's output by providing both a specific solution that satisfies the CF targets, but also a broader assessment of the areas that were deemed important. The best solution and selection frequency maps of this final scenario, as the foundation of the ArcNet PAC network, are given in Fig. S9. The results of all other Marxan scenarios are not provided but are available upon request.

In the fourth cycle, the results of a series of penultimate scenarios were presented to the thematic leads and SC, who then made several strategic decisions concerning: whether targets for the Central Arctic should be increased relative to the remaining bioregions; the final choice of the distinctive target multiplier; and whether existing MPAs should be locked-in for the final set of maps. Based on this feedback, the final Marxan scenario was run. Since Marxan's best solution is simply the configuration of PUs that received the lowest objective function score and is not repeatable due to the random element of simulated annealing, ArcNet's final PAC network was instead based on the selection frequency (Fig. S9b) where all PUs that scored >50% were included in the initial network. From here, several additional steps were required to fine tune the network:

- confirming that conservation targets were met for each CF – where targets fell short (due to the use of selection frequency as the starting point rather than best solution where all targets are met), PUs that had been selected by Marxan in the best solution but that had a selection frequency <50 were added to the network, resulting in a < 1% increase in the network's total area;
- incorporating coastal CFs such as salt marshes, intertidal zones, polar bear denning areas, and other habitats into the network, but excluding all other terrestrial parts of PUs. We also added all areas within existing protected coastal areas;
- manually adjusting several PACs to improve the delineation of the PAC with the coastline – these corrections did not exceed 1% of the total network area; and
- dividing several large, identified areas into two or three smaller areas. While this step was guided largely by geomorphologic or oceanographic features, the primary purpose was to provide more logical divisions to simplify further discussions and analysis. For example, the area covering northeast Greenland was divided in two: one along the northern coast and the second along the eastern coast.

The difference between the initial network and the network after these adjustments is shown in Fig. S10. Finally, as the jagged boundaries of the PACs, which follow the 30 km square edges of the PUs, have no physical meaning and are impractical for implementation and unappealing visually, they were smoothed using the Polynomial Approximation with Exponential Kernel (PAEK) algorithm in ArcGIS with a maximum allowable offset of 50 km.

ArcNet's pathway to implementation

The culmination of ArcNet's pre-emptive network design efforts will be the implementation of an international conservation network across the Arctic in line with the GBF's Target 3. The intention is that ArcNet will help overcome previous barriers to achieving these internationally-agreed biodiversity targets. The operational model of ArcNet's pathway to implementation includes three steps, as illustrated in Fig. 2: dissemination, inclusive engagement, and network design support at finer scales. Here we detail some of ArcNet's ongoing and planned activities in support of timely implementation.

Disseminating ArcNet's vision. The first step of ArcNet's implementation phase is to actively reach out to specific audiences that can support implementation as well as to the broader community concerned with or making decisions about the Arctic Ocean. The goal is to share and generate momentum behind ArcNet's vision for an Arctic conservation network and to build a community that reflects Arctic Ocean knowledge, rights, stakes, and interests. An important objective is the publication of this manuscript in order to reach a broad audience across disciplines, interests, and society. In addition, ArcNet has hosted and will be hosting sessions and workshops at a number of Arctic forums such as Arctic Circle Assembly, Arctic Frontiers, the Fifth International Marine Protected Areas Congress (IMPAC5), and the CBD's and UNFCCC's COPs. In preparation for initiating conversations and information meetings with marine planners and managers in relevant governmental ministries and departments of Arctic coastal states, ArcNet has prepared a glossy guide for dissemination beyond the scientific community. Our overall message is that, through ArcNet, nations can find solutions to fulfilling their GBF commitments.

Inclusive engagement. An effective dissemination campaign will contribute towards broad and inclusive engagement, the next step in ArcNet's implementation pathway. Since completion of the analysis phase, we have begun engaging with key actors, building on existing cooperation and partnerships, with the aim of determining the specific values and interests of all parties. Potential partners have already been identified, and specific asks have been developed (see Table 2). Some specific examples include:

- initiating/formulating proposals to and conversations with national authorities in Arctic coastal states on how ArcNet can be used for national action implementing the GBF's targets;
- engaging directly with Indigenous Peoples and local communities to support and inform local area-based conservation initiatives;
- engaging with marine actors (e.g., lease owners) on mitigating risks from industrial activities in important areas for biodiversity through identifying and cooperating on solutions;
- engaging scientists and building the community of practice, to: formulate guidance on how area-based conservation measures can contribute to biodiversity resilience to ocean change, highlighting both the capabilities of existing measures and the need for new measures; understand how climate-model projected changes shape future ecosystems; and guide proactive and resilient conservation actions;
- alongside Arctic nations and Indigenous organisations, informing projects at the Arctic Council's PAME and CAFF working groups that develop regional support and guidance for implementing the pan-Arctic network in an ecologically compelling, just, and equitable way, with a focus on how Indigenous knowledge can inform network planning and implementation; and
- exploring, with other parties, how obligations under the future HST Agreement⁴² can be implemented in the Central Arctic Ocean, specifically with regard to advancing proposals of marine protected areas and related draft management plans.

Guiding network design. Ultimately, dissemination of ArcNet's vision and inclusive engagement will lead to nationally-sanctioned (globally-sanctioned in the case of HST) network design and implementation exercises based on ArcNet's operational model; the final milestone of implementing an Arctic conservation network built from the bottom up. While value-determined features (e.g., ecosystem services and resources) could not be included as CFs during the design of ArcNet's PAC network due to insufficient participation in these early stages, broad engagement and our operational model provides the basis for such discussions to take place. Here, stacks of services (values), which derive from ecosystem functions, can be integrated into ArcNet's network design, which itself is based on a scientific foundation of agreed conservation criteria and principles in support of biodiversity. Also, the ArcNet tools provide a means to address some of the power issues that come with broad participation in value-related discussions by focusing on the needs of biodiversity from which these values arise. ArcNet thus provides both a

ecological foundation and a socio-political awareness to design for entertaining such value discussions.

Progress towards these network design activities is already underway. Context-specific conservation proposals are currently under development for several ArcNet PACs and blue corridors—migration superhighways for marine megafauna⁵⁷—including fit-for-implementation MPA documentation, stakeholder-agreed zoned MPAs, and Other Effective Area-Based Conservation Measures (OECM). These partnerships between governments and stake- and rights-holders, and the mutually agreed solutions that result will provide the enabling conditions required to accelerate the implementation of conservation measures while building capacity and communities of practice along the way.

Importantly, the ultimate goal, beyond establishing an Arctic conservation network, is to move towards an ocean-scale conservation design approach where we expand our exclusive focus on conserving the “30 per cent” to include planning and management for enabling effective conservation and sustainable usage of the remaining “70 per cent”. After all, the ocean, its ecosystems and biodiversity are all connected. Only a design that considers all these connections and integrates conservation with sustainable use across all ocean space will secure the benefits people receive from the ocean.

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Author contributions

All main authors contributed to the interpretation of results, and all authors contributed to and commented on the manuscript. T.D.J. conceived of and drafted the manuscript and prepared the figures; M.Som. co-led the project and analysis principles development, and contributed to the analysis and manuscript writing; B.S. led the scientific analysis, co-led analysis principles development, oversaw the SAT and thematic groups, and contributed to manuscript writing, web-tool development, and figure preparation; J.M. co-led the project, facilitated all international workshops/meetings, and contributed to the analysis principles; N.P. co-led sea ice biota thematic group, conducted the Marxan analysis, co-developed web-tools, and contributed to data review, and verification; I.O. co-led the project, and contributed to analysis principles; N.C., M.V.G., O.V.S. and V.S. led thematic groups (fish, birds, mammals, and benthos, respectively), and contributed to analysis principles and reviews. M.G. and J.C.R. contributed to analysis principles and participated in workshops; H.R.S. contributed to analysis principles, and reviewed Marxan outputs; J.A.A. reviewed/advised on target setting approach and contributed to analysis principles; M.L.L. contributed review of

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Competing interests

The authors declare no competing interests.

Additional information

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