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Journal

Proceedings of the Royal Society B, 280(1773)

ISSN

0962-8452

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Publication Date

2013-12-22

DOI

10.1098/rspb.2013.1684

Peer reviewed



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Research

Cite this article: Wedding LM, Friedlander AM, Kittinger JN, Watling L, Gaines SD, Bennett M, Hardy SM, Smith CR. 2013 From principles to practice: a spatial approach to systematic conservation planning in the deep sea. *Proc R Soc B* 280: 20131684. <http://dx.doi.org/10.1098/rspb.2013.1684>

Received: 28 June 2013

Accepted: 14 October 2013

Subject Areas:

ecology, environmental science

Keywords:

systematic conservation planning,
marine protected area network, deep sea,
abyssal plains, geographic information system

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From principles to practice: a spatial approach to systematic conservation planning in the deep sea

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Increases in the demand and price for industrial metals, combined with advances in technological capabilities have now made deep-sea mining more feasible and economically viable. In order to balance economic interests with the conservation of abyssal plain ecosystems, it is becoming increasingly important to develop a systematic approach to spatial management and zoning of the deep sea. Here, we describe an expert-driven systematic conservation planning process applied to inform science-based recommendations to the International Seabed Authority for a system of deep-sea marine protected areas (MPAs) to safeguard biodiversity and ecosystem function in an abyssal Pacific region targeted for nodule mining (e.g. the Clarion–Clipperton fracture zone, CCZ). Our use of geospatial analysis and expert opinion in forming the recommendations allowed us to stratify the proposed network by biophysical gradients, maximize the number of biologically unique seamounts within each subregion, and minimize socioeconomic impacts. The resulting proposal for an MPA network (nine replicate 400 × 400 km MPAs) covers 24% (1 440 000 km²) of the total CCZ planning region and serves as example of swift and pre-emptive conservation planning across an unprecedented area in the deep sea. As pressure from resource extraction increases in the future, the scientific guiding principles outlined in this research can serve as a basis for collaborative international approaches to ocean management.

1. Introduction

The deep sea begins at the shelf break (more than –200 m depth) and spans 360 000 000 km² forming the largest environment on the Earth, which harbours both extraordinary biodiversity and supports distinct biological communities containing high levels of endemism [1–4]. The seabed is characterized by a number of unique habitats and ecosystem types, including abyssal plains, seamounts, hydrothermal vents and cold seeps [1,5,6]. In addition, commercially valuable mineral resources, including nickel- and copper-rich manganese nodules and cobalt-rich crusts, are also present in these environments [7,8]. Recent advances in technological capabilities have led to competing spatial demands between conservation of the unique deep-sea ecosystems and economic mining interests. These competing spatial interests are complicated by the consideration that deep-sea biota are particularly vulnerable

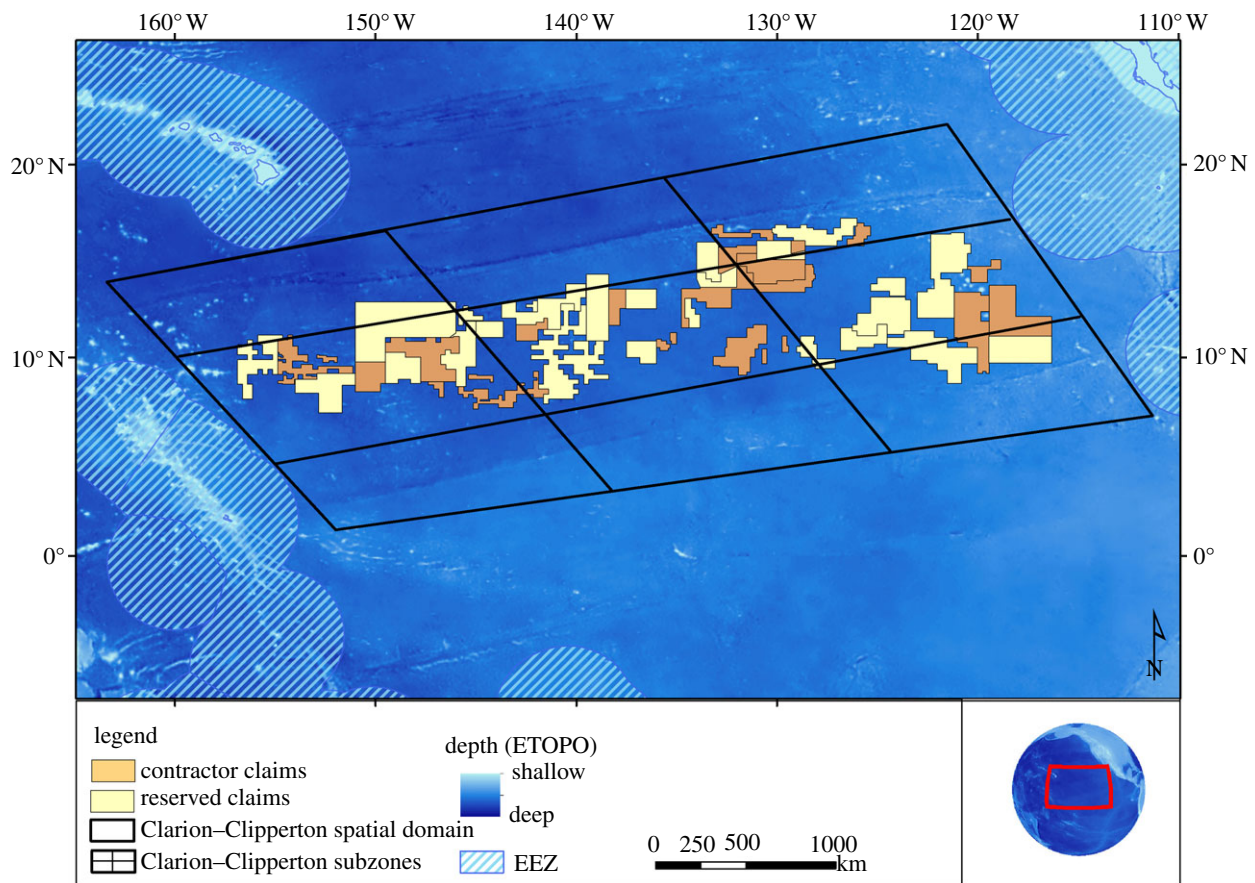


Figure 1. Spatial domain of the study area, nine replicate blocks to guide the MPA replicate placement, and location of mining claims in the Clarion–Clipperton fracture zone.

to the impacts of extractive activities owing to slow growth rates and delayed maturity [9,10].

In light of the vulnerability of these unique ecosystems, it is critical to conserve areas of the deep sea in the face of imminent resource extraction. The Clarion–Clipperton fracture zone (CCZ) in the equatorial North Pacific is a focal area for mining interests, and mining operations are expected to be initiated in the CCZ by 2025 [10]. The CCZ is estimated to contain 340 million tonnes of nickel and 265 million tonnes of copper [8]. Mining of abyssal manganese nodules will affect large areas of the seafloor owing to direct mining disturbance (estimated scales of 300–600 km² per year) and re-deposition from sediment plumes (over scales of 10–100 km from the mining site; see [11–14]).

The seabed of the CCZ is located beyond national jurisdictions and has been declared the ‘common heritage of mankind’ by the United Nations General Assembly and the parties to the Third United Nations Convention on the Law of the Sea [15,16]. The International Seabed Authority (ISA) is tasked with developing rules and regulations for exploration and extraction of minerals from the deep sea [17], and is required to use the precautionary approach, as reflected in Principle 15 of the Rio Declaration. The Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area stipulate that prior to the issuance of test-mining and exploitation permits, MPAs (e.g. ‘preservation reference areas’) will be delineated ‘in which no mining will occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment’ [18, p. 20]. Regulations for management of mining impacts clearly identify a requirement for MPAs, and establish an

opportunity for spatial ecosystem-based management. In the case of the CCZ, an established MPA network has social advantages in reducing uncertainty about future restrictions among mining contractors and would assist in guiding the mining industry in minimizing impacts to the marine environment during resource extraction [19]. Establishing protections at the international scale would also represent a major marine management accomplishment in areas beyond national jurisdiction, which has been the focus of much discussion for conservation action [20,21].

Here, we describe an expert-driven systematic conservation planning process that was used as part of a collaborative stakeholder initiative to develop science-based recommendations for the establishment of a network of MPAs in the deep sea. The stakeholders developed these recommendations by applying ecosystem-based management principles together with spatial analysis of biophysical and social datasets, which helped assess trade-offs in the planning region and ultimately select an approach that best balanced the competing interests of biodiversity protection and resource use. We show how this integrated approach has global implications for conservation in areas beyond national jurisdiction, and how similar approaches can be used to implement ecosystem-based approaches in systematic conservation planning processes elsewhere.

The planning region is located in the eastern central Pacific Ocean (figure 1 and table 1), and is bounded to the north and south by the Clarion–Clipperton fracture zones. The planning region spans approximately 6 000 000 km² and encompasses a broad range of habitat types, including abyssal plains and hills, seamounts and fracture zones. The majority of the planning region lies in areas beyond national

Table 1. GIS datasets used in spatially articulating guiding principles for deep-sea MPA network design.

data layer	units	strata
mining claims	km ²	contractors reserved
seamounts	M	<200 m 200–1000 m 1000–2000 m >2000 m
nitrogen flux	mmol N cm ⁻² d ⁻¹	100 m 200 m 500 m
bathymetry	M	continuous
polymetallic nodule abundance	kg m ⁻²	continuous
EEZ	km ²	
macro invertebrate abundance		continuous

jurisdiction, resulting in a diversity of stakeholder interests that needed to be incorporated into the MPA network design process, including the policy leaders from the ISA, UNCLOS signatories, nodule mining claim holders, NGOs, marine scientists, legal experts and mining experts.

2. Systematic conservation planning in the deep sea: a collaborative approach

Systematic conservation planning involves the development of quantitative conservation objectives, usually based on robust ecological assessments that underpin the design and implementation of spatial conservation areas [22]. The ecological assessments used to inform these quantitative conservation objectives rely on well-established methods to document patterns of biodiversity, habitat distribution, other critical biophysical attributes, as well as guiding frameworks to include these assessments into conservation planning to set targets and develop action plans [22,23]. However, for these methods to be effective, they need to be adapted to the specific ecological and socioeconomic context of a planning region (e.g. the deep sea). Systematic conservation planning was first applied successfully for terrestrial conservation [24] and has since been applied in the coastal environment [23,25]. Recently, a systematic conservation planning framework was outlined for the high seas [26], and several examples exist in which this approach has been applied in practice [27,28].

To develop guidelines for conservation planning in the deep sea, a workshop was convened with the support of the Pew Fellows Programme in Marine Conservation, as well as Census of the Diversity of Abyssal Marine Life (CeDAMar) and Global Census of Marine Life on Seamounts (CenSeam). The goals of the workshop were to develop recommendations regarding the creation of a network of MPAs for the ISA to consider for implementation in the

CCZ. In order to address this aim, the workshop was organized in three stages. First, a panel of scientists and legal experts reviewed the general principles of MPA network design, the legal framework of environmental protection in the high seas and conservation activities in the deep sea and areas beyond national jurisdictions to date. The second stage of the workshop concentrated on identifying and characterizing the distribution of anthropogenic threats (e.g. mining, fishing, etc.) to deep-sea biodiversity and developing a robust ecological assessment of the key physical, biogeographic, ecological and biodiversity features in the planning region. The final stage focused on applying the MPA network design principles to the ecological assessment to develop a series of management alternatives.

The workshop was specifically designed to be participatory in nature to ensure that all stakeholder interests were 'at the table' in negotiating both the design principles and in reviewing assessments and alternatives to be incorporated into the design process. Workshop participants comprised experts representing the interests of a broad consortium of stakeholders, including the ISA, consultants, non-governmental organizations and the scientific research community. Through this participatory process, a series of general, scientific-based design guidelines were developed. Below, we describe the specific steps applied during the systematic conservation planning process and discuss how the MPA network design principles and ecological assessment coalesced into an ecosystem-based management recommendation to the ISA for the CCZ.

3. Developing design principles for a marine protected area network in the deep sea

We relied on a set of design principles that were initially developed to guide the establishment of networks of coastal MPAs [29–31], and workshop experts worked to adapt these guidelines to the biophysical, socioeconomic and governance context of the deep sea. These principles have since been further developed as guidance for ecosystem-based management approaches in the open ocean [32–34]. Below, we outline these design principles and highlight the key literature on marine ecosystem-based management and the deep sea that informed their development.

- (1) *Marine protected area (MPA) design and implementation should fit into the existing legal framework of the International Seabed Authority for managing seabed mining and protecting the marine environment.* The ISA's mandate requires that preservation reference zones (i.e. MPAs) are delineated where mining may not occur [17]. In addition, the ISA is tasked with using the precautionary approach and ensuring the effective protection of the marine environment from harmful effects arising from mining activities. Therefore, recommendations should be developed such that they are consistent with the mission, regulations and policy processes of the ISA, to ensure maximum likelihood of consideration and adoption.
- (2) *To the extent that it is scientifically sound, the proposed network should minimize socioeconomic impacts.* The MPA network should ideally be designed to have minimal overlap with the existing spatial footprint of nodule mining claims granted by the ISA up to 2007 (the time

of the workshop), thus minimizing socioeconomic impacts to mining contractors. The network design should be flexible in the location of specific MPAs to allow input from potentially affected stakeholders (e.g. mining contractors), and to allow reserve locations, size or boundaries to be altered as claim areas change in location and number (i.e. be adaptable in response to socioeconomic concerns).

- (3) *The MPA network should maintain sustainable, intact and healthy marine populations in the planning region.* The MPA network should provide large-scale ecosystem benefits to deep-sea biota and protect all species, life stages and critical habitats necessary for deep-sea biota [35,36]. The network should protect all the different habitat types in the planning region, and should place under protection replicates of habitat types to ensure persistence and enshrine complementarity in the network.
- (4) *The MPA network should take into account biophysical gradients which affect the biogeography of marine biodiversity in the planning region.* In reserve networks that span broad geographical areas, biogeographic representation is one of the key ecological design criteria and supports the goal of maximizing the protection of biodiversity [37]. The CCZ region should be divided into three east–west and three north–south strata for conservation management, because strong productivity-driven gradients drive patterns of marine biodiversity from east to west and south to north [14,38]. Representative reserves should be located in each of the nine resultant subregions.
- (5) *Each MPA should protect a full range of habitat types found within each subregion.* To preserve representative and unique habitats, all habitat types for a subregion should be included within an MPA. A variety of general habitat types can be recognized within the CCZ, including abyssal plains/abyssal hills, seamounts and fracture zones. Most of these habitats are continuously distributed across the region, except for seamounts. Seamounts are isolated features hosting vulnerable benthic communities, which can be rapidly and severely impacted by human activities [39]. Seamount communities, in particular, have a high potential to be impacted by midwater sediment plumes, which may disperse large distances [11]. Thus, it is recommended that as many seamounts from a subregion as possible (with a target of at least 40%), and portions of known fracture zones, be included within MPAs.
- (6) *Each MPA should be large enough to maintain minimum viable population sizes for species potentially restricted to a subregion.* For the CCZ, this requires that protected areas be at least 200 km in length and width (40 000 km²). Macrofaunal and meiofaunal invertebrates constitute the vast majority of biodiversity in the CCZ and almost certainly include species with the most limited dispersal capabilities and biogeographic ranges. A number of studies in shallow-water habitats suggest that mean dispersal distance for most benthic invertebrate species is less than 100 km [40,41]. Available current-metre data from the CCZ [14] indicate that the physical transport processes at the abyssal seafloor in the CCZ are weaker than in most shallow-water settings, suggesting that mean dispersal distance for most benthic species will be similar to or smaller than that of shallow-water species. To ensure persistence of populations without the certainty of larval recruitment from elsewhere, a substantial fraction of dispersing larvae

and adults of targeted species must remain within an MPA. To this end, an accepted conservation approach is to make the length and width of the MPA at least two times the mean faunal dispersal distance [40]. This indicates a size of the core area of each MPA of 200 × 200 km.

- (7) *Each MPA should be surrounded by a buffer zone to insure that biota and habitats in the protected area are not affected by anthropogenic threats occurring outside the MPA.* Nodule mining is expected to produce two types of sediment plumes that may impact benthic habitats: (i) near-bottom plumes created by tailings from the mining head during nodule extraction from the seafloor; and (ii) plumes in the water column derived from sediments attached to nodules during lifting from the seabed [42]. Over a broad range of hydrodynamic conditions, more than 99% of the mass of the near-bottom sediment plumes is expected to settle within one month and within 100 km of the mining head [11]. *In situ* tracer studies and advection–diffusion models also suggest dispersal scales for neutrally buoyant particles of less than 100 km over timescales of one to two months in abyssal ecosystems [43,44]. On timescales of weeks to months, and sometimes even years, the mean abyssal velocities in most regions of the deep sea are dominated by meso-scale eddies [45], implying that there is no defined ‘downstream’ direction, i.e. the sediment plumes generated by mining can travel in any direction. Seamount communities have a high potential to be impacted by mid-water sediment plumes, which may disperse large distances (e.g. 100 km; [42]). Thus, a buffer zone of 100 km around an MPA is required to protect the core area from significant impacts from near-bottom sediment plumes, which may come from any direction. This results in a 200 × 200 km core protected area surrounded by a 100 km buffer zone, resulting in a 400 × 400 km (160 000 km²) MPA. The boundaries will be straight lines that will facilitate recognition, monitoring and enforcement of the MPA network.
- (8) *The boundaries of MPA should be straight lines to facilitate rapid recognition and compliance.* The use of straight-line boundaries is a basic principle of the design of MPAs that facilitates recognition, compliance and enforcement of MPAs [46].

(a) A spatial approach to ecosystem assessment in the deep sea

Moving towards ecosystem-based management requires comprehensive ecosystem assessments to characterize planning regions and develop conservation planning targets [34]. Ecosystem assessments are defined as a ‘formal synthesis and quantitative analysis of information on relevant natural and socioeconomic factors, in relation to specified ecosystem management objectives’ [47]. Such assessments are recognized as a critical step in systematic conservation planning, and provide critical information to inform planning targets (e.g. protecting 20% of a given area) and the spatial design of MPA networks [22,23]. The first step in our ecosystem assessment in the CCZ region was to define the spatial domain that bordered, but did not overlap with any EEZs in the region (figure 1). The spatial domain covered

Table 2. Summary statistics for chemical, physical and geological information associated with Clarion–Clipperton spatial domain. ‘N flux’ represents the vertical flux of organic nitrogen in sinking particulate material.

attributes	units	range	mean (s.d.)	n
N flux 100 M	mmol N cm ⁻² d ⁻¹	0.18–4.04	1.46 (0.73)	77 861
N flux 200 M	mmol N cm ⁻² d ⁻¹	0.07–1.43	0.52 (0.26)	77 861
N flux 500 M	mmol N cm ⁻² d ⁻¹	0.01–0.11	0.04 (0.02)	77 861
nodule abundance	kg m ⁻²	0.01–39.69	4.90 (3.26)	77 861
depth	metres	578–6560	4793.91 (463.94)	569 364

approximately 6 000 000 km² of the deep sea in depths ranging between 4000 and 6000 m. Spatial datasets that represented biological and physical characteristics of the CCZ were synthesized from a variety of sources and included (i) bathymetry (m); (ii) seamounts; (iii) organic nitrogen flux (mmol N cm⁻² d⁻¹) in sinking particulate organic carbon, i.e. an index of food availability in the detritus based deep sea; (iv) polymetallic nodule abundance (kg m⁻²); and (v) macroinvertebrate abundance (table 2 and figure 2). Organic nitrogen flux (mmol N cm⁻² d⁻¹) was derived from Yool *et al.*'s [48] production model at three depth ranges (100, 200 and 500 m). A nearest neighbour interpolation was conducted in ARCGIS SPATIAL ANALYST on the macrofaunal and polymetallic nodule abundance datasets (10 km grid size) in order to provide a continuous raster surface of abundance across the EEZ.

There are strong north–south and east–west gradients in productivity in the CCZ [6,14,38,49], and these gradients drive major changes in benthic community composition across the region [49]. The fauna of the CCZ exhibits high species diversity (especially in the macrofauna and meiofauna), and there is large variation in community structure from east to west and south to north [49–51]. To address the strong productivity-driven gradients in ecosystem structure in the replicate network design, the spatial domain was split into a 3 × 3 block design placement [49,51]. This large MPA network is not a true replicate network in the sense that the communities are expected to have a high degree of larval transport and interconnection; however, the replicates were applied as an insurance policy.

Bathymetry was derived from the National Geophysical Data Center ETOPO2 Global 2' Elevations dataset from September 2001. Seamount data were acquired from the Sea Around Us Project, which inferred possible seamount locations from the ETOPO2 data [52]. Seamount data were binned into strata of seamount depth ranges to ensure MPA design incorporated a diversity of seamount depth ranges and associated faunal assemblages. The number of seamounts in each of the proposed MPA networks ranged from 36 to 42 in total. The first proposed MPA network protected a greater number of seamounts than the other two, but it only encompassed seamounts with summit depths more than 2000 m. Although MPA scenario 2 and 3 included fewer seamounts, they both incorporated seamounts within multiple ranges of summit depth (e.g. –1000 to 2000 and more than –2000 m) that likely would protect a greater diversity of species.

All spatial datasets were synthesized in geographical information systems (GIS) to form the basis for the spatial ecosystem

assessment and inform the systematic conservation planning process. A synthesis of biophysical characteristics, such as organic nitrogen flux (mmol N cm⁻² d⁻¹) at –100, –200 and –500 m, as well as depth and nodule abundance, was derived for each MPA design scenario to support the ISA's evaluation of the proposed networks (table 3). The design principles were applied to the final spatial ecosystem assessment to support the development of proposed MPA network configurations. The spatially explicit nature of a majority of the design principles supported the direct transfer of principles to proposed MPA map products for submission to the ISA. Design principles were used in conjunction with the spatial ecosystem assessment to develop three MPA network configurations (figure 3). These alternatives operationalized the network design principles and the ecological assessment, and were developed in a manner consistent with the regulations and policy context of the ISA.

4. Moving from principles to practice: insights from an expert-driven process

Recovery from mining impacts in the CCZ will require decades or more for soft-sediment fauna and thousands to millions of years for biota specializing on manganese nodules [10,13,14,53,54]. The slow ecosystem recovery rates at the abyssal seafloor make it likely that the environmental impacts of large-scale mining will be widespread across the CCZ before any single location recovers. It is therefore critical to conserve areas of the deep sea in the face of imminent resource extraction. The proposed MPA alternatives describes a network of MPAs that cover 24% of the total 6 000 000 km² CCZ management area. In 2007, claim areas constituted about 19% of this total area, and the alternatives were optimized in their placement so as to minimize socioeconomic impacts while still adhering to design principles that would ensure a scientifically sound biodiversity conservation outcome. This alternative balances the competing interests of biodiversity protection and resource use, resulting in an efficient allocation that maximizes benefits and minimizes the costs to mining claims. Developing analyses that accurately assess trade-offs while optimizing outcomes can help support ecosystem-based management approaches in ocean environments [55]. This is even more pressing for the CCZ considering that, mining claim licences continue to be granted by the ISA, with five new claims of 150 000 km² each granted since 2007, putting more than 30% of the management area within mining claims (<http://www.isa.org.jm/files/images/maps/CCZ-Sep2012-Official.jpg>).

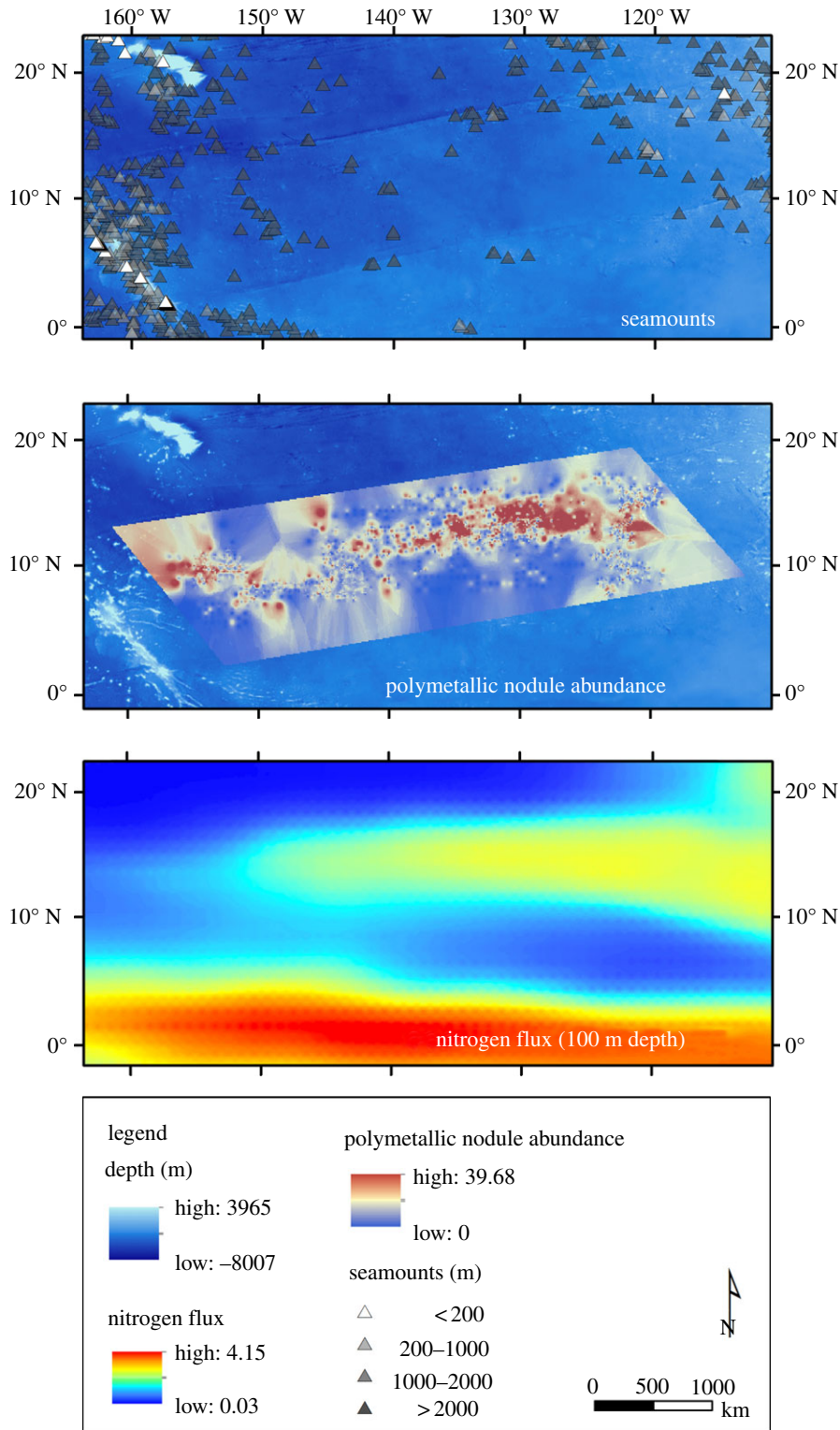


Figure 2. Map of Clarion–Clipperton fracture zone spatial datasets including bathymetry derived from the ETOPO2 Global 2' Elevations dataset, seamount data acquired from the Sea Around Us Project, nitrogen flux ($\text{mmol N cm}^{-2} \text{d}^{-1}$) from Yool *et al.* [48] and polymetallic nodule abundance datasets (10 km grid size).

Mapping geomorphic features (e.g. seamounts) and dynamic oceanographic characteristics (e.g. primary production at multiple depth zones) were useful in ensuring that the guiding scientific principles were implemented in a spatial framework. The challenges of implementing a geospatial approach in the deep sea and open ocean can be great, given the lack of comprehensive biological data [56], the logistics of managing a large, dynamic MPA far from shore [57], and the uncertainty surrounding

connectivity and recovery timescales in these areas [58]. The acquisition of such data at these broad spatial scales would have been cost prohibitive only a few years ago [59]. These spatial datasets can be used as proxies for species distribution and make up for the lack of *in situ* biological assessments in the abyssal plains, seamounts and on the high seas. Continued efforts to map and monitor dynamic oceanographic characteristics and static geomorphic features across space and time will provide a

Table 3. Summary statistics for chemical, physical, and geological information associated with three proposed MPA design scenarios. 'N flux' represents the vertical flux of organic nitrogen in sinking particulate material.

attribute		MPA design 1	MPA design 2	MPA design 3
N flux 100 M	range	1.02–1.91	0.94–1.45	0.92–1.73
mmol N cm ⁻² d ⁻¹	mean (s.d.)	1.37 (0.24)	1.22 (0.13)	1.29 (0.22)
N flux 200 M	range	0.35–0.68	0.33–0.51	0.33–0.62
mmol N cm ⁻² d ⁻¹	mean (s.d.)	0.48 (0.09)	0.43 (0.05)	0.46 (0.08)
N flux 500 M	range	0.03–0.05	0.03–0.04	0.03–0.05
mmol N cm ⁻² d ⁻¹	mean (s.d.)	0.04 (0.01)	0.03 (0.01)	0.04 (0.01)
nodule abundance	range	0.78–13.82	3.06–9.50	1.55–12.44
kg m ⁻²	mean (s.d.)	5.15 (1.87)	5.24 (0.98)	5.16 (1.93)
depth (m)	range	3280–5268	3409–5431	3560–5245
	mean (s.d.)	4773 (192)	4897 (190)	4719 (187)
seamounts	<2000 m	0	4	3
	>2000 m	42	33	33

strong foundation to support growing efforts to spatially manage the deep sea and open ocean [6,60,61].

An interdisciplinary framework, supported by an empirically driven geospatial approach, reinforced a planning process that effectively balanced biodiversity conservation and socioeconomic goals. The broad group of specialists that engaged in the planning process represented different areas of expertise and interests, and a collaborative workshop environment engendered direct communication and collaboration among participants, including resource managers at the ISA, throughout the process. This approach allowed for the guiding scientific principles established at the workshop to be spatially articulated. The value of using a geospatial approach was clearly demonstrated as it allowed for the consideration of recommended MPA locations to protect as many seamounts within a subregion as possible, gave us the ability to stratify the proposed network by biophysical gradients (e.g. productivity, faunal assemblage structure and turnover, etc.), minimize overlap with existing mining exploration and reserved claim areas, and mitigate the potential impacts of sediment plumes from deep-sea mining. Sound scientific consideration guided the spatial approach in this work and demonstrated the importance of the essential and iterative link between biological, socioeconomic and geospatial experts.

This expert-driven systematic conservation planning process demonstrates how collaborative development of scientific guiding principles supported the creation of MPA alternatives that addressed the competing interests of biodiversity protection and resource use. Following the development and submission of these recommendations [62], in July 2012, the ISA adopted an environmental management plan for the CCZ to be implemented on a provisional basis for 3 years. The management plan includes the designation of nine 400 × 400 km 'Areas of Particular Environmental Interest' that are closed to mining claims (ISBA/18/C/22). The distribution of the ISA's 'Areas of Particular Environmental Interest' (<http://www.isa.org.jm/files/images/maps/CCZ-Sep2012-Official.jpg>) closely resembles the MPA design scenario presented in our figure 3a, with MPA 8 shifted to the northeast. If the ISA permanently adopts these 'Areas of Particular Environmental Interest' as areas protected from

mining, then it will set a major international precedent in marine management in areas beyond national jurisdiction.

5. Conclusion

The framework developed in this systematic conservation planning process for establishing preservation reference zones provided a unique and unprecedented opportunity for stakeholders to design a network of MPAs prior to the initiation of extraction activities and the further granting of mineral exploration leases. The establishment of MPAs prior to extraction is significant as it may be more challenging to establish MPAs after resource extraction begins [58]. Furthermore, establishing a network of deep-sea MPAs would help meet important environmental and social goals. A large-scale protected area network would ensure that biodiversity and ecosystem function are safeguarded from mining, and could be designed to fulfil international commitments to sustainable development expressed in the United Nations Rio +20 Conference on Sustainable Development, as well as provisions of the Convention on Biological Diversity calling for the protection of biological diversity [63,64]. Implementation of an MPA network as an *a priori* conservation action also provides a buffer against current or future environmental threats and should be designed to mitigate those perceived threats [35]. Furthermore, the establishment of the MPA network may reduce uncertainty about future restrictions among mining contractors, protecting existing claims and economic investments in these claims.

This integrated and collaborative approach has global implications for conservation in areas beyond national jurisdiction or other complex ocean zones, and similar approaches may be useful for implementing ecosystem-based approaches in systematic conservation planning processes. The proposed CCZ MPA network (1 440 000 km²) is approximately four times the size of the Great Barrier Reef Marine Park (345 400 km²) and will be a significant addition to the large global MPAs in the Pacific Ocean. Assuming that the ISA permanently protects its system of nine 'Areas of Particular Environmental Interest'

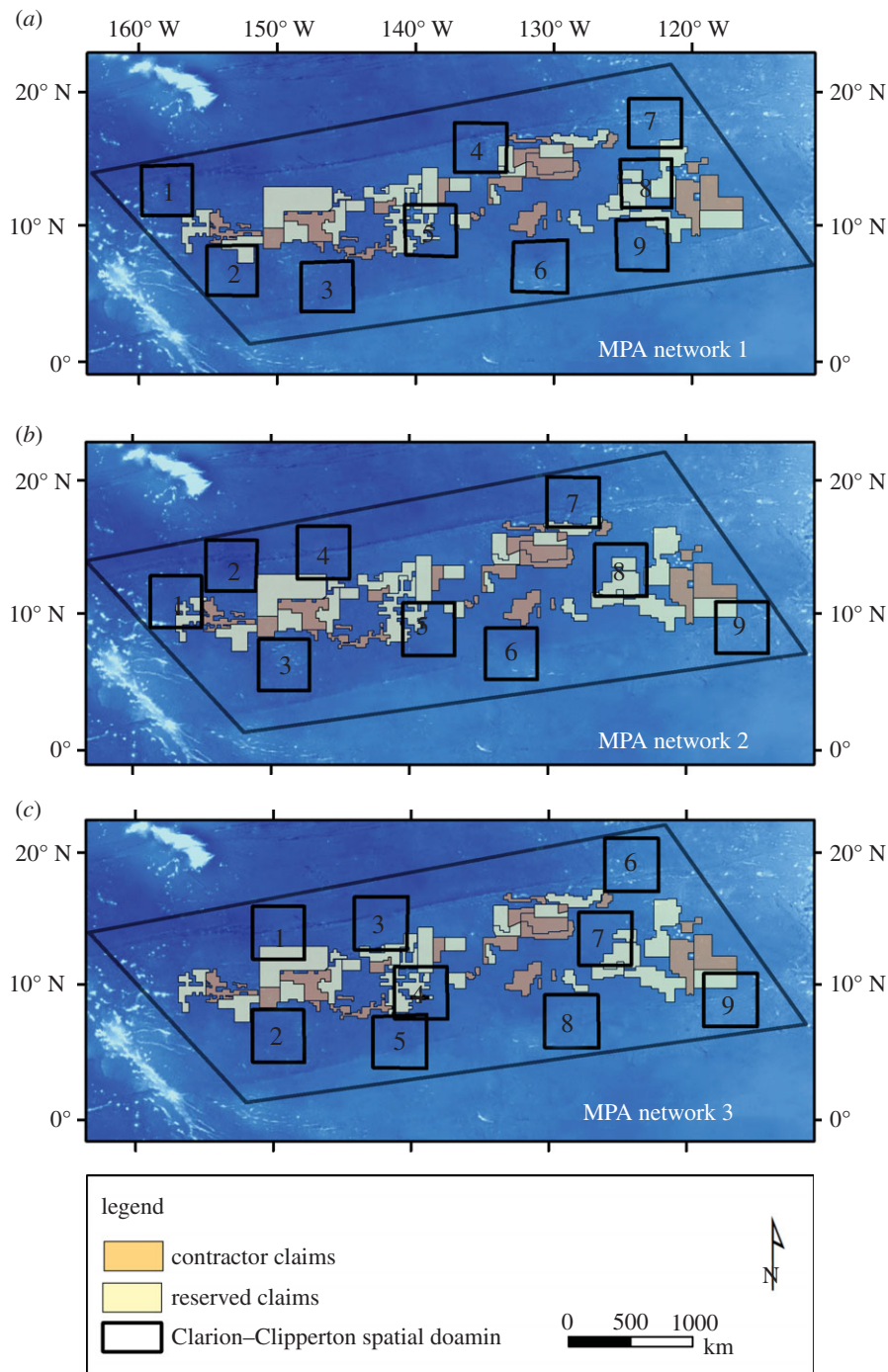


Figure 3. Map of the three proposed MPA design scenarios submitted to the International Seabed Authority. (a) Closely resembles the distribution of ‘Areas of Particular Environmental Interest’ provisionally adopted by the ISA in 2013 as areas in which mining claims are precluded (see <http://www.isa.org/jm/files/images/maps/CCZ-Sep2012-Official.jpg>).

from mining activities, an important precedent will be set in applying swift and pre-emptive management actions across an unprecedented expanse of the deep sea.

Acknowledgements. We are very grateful to all the participants in the workshop on *Design of Marine Protected Areas for Seamounts and the*

Abyssal Nodule Province in Pacific High Seas, held in Honolulu 23–26 October, 2007. This is SOEST publication no. 9025.

Funding statement. This work was made possible by a Pew Fellowship in Marine Conservation to C.R. Smith, and by funding provided by the Census of Diversity of Abyssal Marine Life (CeDAMar), CenSeam, and the ISA.

References

- Smith CR, Demopoulos AWJ. 2003 Ecology of the deep Pacific ocean floor. In *Ecosystems of the world: ecosystems of the deep ocean*, vol. 28 (ed. PA Tyler), pp. 179–218. Amsterdam, The Netherlands: Elsevier.
- Tyler PA ed. 2003 *Ecosystems of the world*, vol. 28. *Ecosystems of the deep ocean*, pp. 5–39. Amsterdam, The Netherlands: Elsevier.
- Pitcher T *et al.* 2006 *Seamounts: ecology, fisheries and conservation*, p. 536. Oxford, UK: Blackwell.
- Davies AJ, Roberts JM, Hall-Spencer J. 2007 Preserving deep-sea natural heritage: emerging issues in offshore conservation and management. *Biol. Conserv.* **138**, 299–312. (doi:10.1016/j.biocon.2007.05.011)

5. Smith CR, De Leo FC, Bernardino AF, Sweetman A, Arbizu P. 2008 Abyssal food limitation, ecosystem structure and climate change. *Trends Ecol. Evol.* **23**, 518–528. (doi:10.1016/j.tree.2008.05.002)
6. Watling L, Guinotte J, Clark MR, Smith CR. 2013 Proposed biogeography of the deep ocean floor. *Prog. Oceanogr.* **111**, 91–112. (doi:10.1016/j.pocean.2012.11.003)
7. Sanders HL. 1968 Marine benthic diversity: a comparative study. *Am. Nat.* **102**, 243–282. (doi:10.1086/282541)
8. Ebbe B *et al.* 2010 Diversity of abyssal marine life. In *Life in the world's oceans: diversity, distribution, and abundance* (ed. A. McIntyre), pp. 139–160. Oxford, UK: Blackwell.
9. Roberts CM. 2002 Deep impact: the rising toll of fishing in the deep sea. *Trends Ecol. Evol.* **17**, 242–245. (doi:10.1016/S0169-5347(02)02492-8)
10. Smith CR, Levin LA, Koslow A, Tyler PA, Glover AG. 2008c The near future of deep seafloor ecosystems. In *Aquatic ecosystems: trends and global prospects* (ed. N. Polunin), pp. 334–351. Cambridge, UK: Cambridge University Press.
11. Rolinski S, Segschneider J, Sundermann J. 2001 Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. *Deep-Sea Res. II* **48**, 3469–3485. (doi:10.1016/S0967-0645(01)00053-4)
12. Thiel H. 2001 Use and protection of the deep sea: an introduction. *Deep-Sea Res. II* **48**, 3427–3431. (doi:10.1016/S0967-0645(01)00050-9)
13. Glover AG, Smith CR. 2003 The deep seafloor ecosystem: current status and prospects for change by 2025. *Environ. Conserv.* **30**, 1–23. (doi:10.1017/S0376892903000225)
14. Hannides A, Smith CR. 2003 The northeast abyssal Pacific plain. In *Biogeochemistry of marine systems* (eds KB Black, GB Shimmield), pp. 208–237. Boca Raton, FL: CRC Press.
15. Baslar K. 1998 *The concept of the common heritage of mankind in international law*. The Hague, The Netherlands: Kluwer Law International.
16. UNCLOS III. 1970 Article 136 declaration of principles governing the seabed and the ocean floor, and subsoil thereof, beyond the limits of national jurisdiction. *G.A. Res.* 2749.
17. ISA. 2000 ISA's regulations for prospecting and exploration of polymetallic nodules in the area <http://www.isa.org.jm/files/documents/EN/Regs/MiningCode.pdf>.
18. ISBA/6/A/18 Annex, regulation 31, part 7, p. 20, 2000.
19. Halfar J, Fujita RM. 2002 Precautionary management of deep sea mining. *Mar. Policy* **26**, 103–106. (doi:10.1016/S0308-597X(01)00041-0)
20. Sumaila UR, Zeller D, Watson R, Alder J, Pauly D. 2007 Potential costs and benefits of marine reserves in the high seas. *Mar. Ecol. Prog. Ser.* **345**, 305–310. (doi:10.3354/meps07065)
21. Ardron J, Gjerde K, Pullen S, Tilot V. 2008 Marine spatial planning in the high seas. *Mar. Policy* **32**, 832–839. (doi:10.1016/j.marpol.2008.03.018)
22. Margules CR, Pressey RL. 2000 Systematic conservation planning. *Nature* **405**, 243–253. (doi:10.1038/35012251)
23. Pressey RL, Bottrill MC. 2009 Approaches to landscape-and seascape-scale conservation planning: convergence, contrasts and challenges. *Oryx* **43**, 464–475. (doi:10.1017/S0030605309990500)
24. Bottrill MC, Pressey RL. 2012 The effectiveness and evaluation of conservation planning. *Conserv. Lett.* **5**, 407–420. (doi:10.1111/j.1755-263X.2012.00268.x)
25. Fernandez L *et al.* 2005 Establishing representative no-take areas in the Great barrier reef: large-scale implementation of theory on marine protected areas. *Conserv. Biol.* **19**, 1733–1744. (doi:10.1111/j.1523-1739.2005.00302.x)
26. Ban NC *et al.* 2013 Systematic conservation planning: a better recipe for managing the high seas for biodiversity conservation and sustainable use. *Conserv. Lett.* **2**, 206–215. (doi:10.1111/conl.12010)
27. O'Leary B, Brown R, Johnson D, von Nordheim H, Ardron J, Packeiser T, Roberts CM. 2012 The first network of marine protected areas (MPAs) in the high seas: the process, the challenges and where next. *Mar. Policy* **36**, 598–605. (doi:10.1016/j.marpol.2011.11.003)
28. Österblom H, Sumaila UR, Bodin A, Hentati Sundberg J, Press AJ. 2010 Adapting to regional enforcement: fishing down the governance index. *PLoS ONE* **5**, e12832. (doi:10.1371/journal.pone.0012832)
29. NCEAS (National Center for Ecological Analysis and Synthesis). 2001 Scientific consensus statement on marine reserves and marine protected areas. *J. Int. Wildl. Law Policy* **4**, 87–90. (doi:10.1080/13880290109353975)
30. PISCO. 2002 *The science of marine reserves* <http://www.piscoweb.org>. 22 pp.
31. Ecological Applications. 2003 *The science of marine reserves*. *Ecol. Appl.* **13**, 228.
32. Norse EA, Crowder LB, Gjerde K, Hyrenbach D, Roberts C, Safina C, Soulé ME. 2005 Place-based ecosystem management in the open ocean. In *Marine conservation biology: the science of maintaining the sea's biodiversity* (eds EA Norse, LB Crowder), pp. 302–327. Washington, DC: Island Press.
33. Foley MM *et al.* 2010 Guiding ecological principles for marine spatial planning. *Mar. Policy* **34**, 955–966. (doi:10.1016/j.marpol.2010.02.001)
34. Foley MM, Armsby MH, Prahler EE, Caldwell MR, Erickson AL, Kittinger JN, Crowder LB, Levin PS. 2013 Improving ocean planning through the use of key ecological principles and integrated ecosystem assessments. *Bioscience* **63**, 619–631. (doi:10.1525/bio.2013.63.8.5)
35. Gaines SD, White C, Carr MH, Palumbi SR. 2010 Designing marine reserve networks for both conservation and fisheries management. *Proc. Natl Acad. Sci. USA* **107**, 18 286–18 293. (doi:10.1073/pnas.0906473107)
36. Grorud-Colvert K, Claudet J, Carr M *et al.* 2011 Networks: the assessment of marine reserve networks: Guidelines for ecological evaluation. In *Marine protected areas: a multidisciplinary approach* (ed. J. Claudet), pp. 293–321. Cambridge, UK: Cambridge University Press.
37. Gilman E, Dunn D, Read A, Hyrenbach KD, Warner R. 2011 Designing criteria suites to identify discrete and networked sites of high value across manifestations of biodiversity. *Biodivers. Conserv.* **20**, 3363–3383. (doi:10.1007/s10531-011-0116-y)
38. Smith CR, Berelson W, DeMater DJ, Dobbs FC, Hammond D, Hoover DJ, Pope RH, Stephens M. 1997 Latitudinal variations in benthic processes in the abyssal equatorial Pacific: controls by biogenic particle flux. *Deep-Sea Res. II* **44**, 2295–2317. (doi:10.1016/S0967-0645(97)00022-2)
39. Clark MR *et al.* 2010 The ecology of seamounts: structure, function, and human impacts. *Annu. Rev. Mar. Sci.* **2**, 253–278. (doi:10.1146/annurev-marine-120308-081109)
40. Botsford LW, Hastings A, Gaines S. 2001 Dependence of sustainability on the configuration of marine reserves and larval dispersal distance. *Ecol. Lett.* **4**, 144–150. (doi:10.1046/j.1461-0248.2001.00208.x)
41. Kinlan BP, Gaines SD. 2003 Propagule dispersal in marine and terrestrial environments: a community perspective. *Ecology* **84**, 2007–2020. (doi:10.1890/01-0622)
42. Oebius HU, Becker HJ, Rolinski S, Jankowski JA. 2001 Parametrization and evaluation of marine environmental impacts produced by deep-sea manganese nodule mining. *Deep-Sea Res. II* **48**, 3453–3467. (doi:10.1016/S0967-0645(01)00052-2)
43. Ledwell JR, Montgomery ET, Polzin KL, St. Laurent LC, Schmitt RW, Toole JM. 2000 Evidence for enhanced mixing over rough topography in the abyssal ocean. *Nature* **403**, 179–182. (doi:10.1038/35003164)
44. Thurnherr AM. 2004 The physical environment of polymetallic sulphides deposits, the potential impact of exploration and mining on this environment, and data required to establish environmental baselines in exploration areas. International Seabed Authority Guidelines for Sulphides Deposits and Cobalt-Crust Mining (Workshop Report).
45. Speer KG, Maltrud ME, Thurnherr AM. 2003 A global view of dispersion above the Mid-ocean ridge. In *Energy and mass transfer in marine hydrothermal systems*, vol. 89 (eds PE Halbach, V Tunncliffe, JR Hein), pp. 287–302. Berlin, Germany: Dahlem University Press.
46. Sladek-Nowlis J, Friedlander A. 2005 *Marine reserve function and design for fisheries management*. Washington, DC: Island Press.
47. Levin PS, Fogarty MJ, Murawski SA, Fluharty D. 2009 Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biol.* **7**, e1000014. (doi:10.1371/journal.pbio.1000014)
48. Yool A, Martin AP, Fernandez C, Clark DR. 2007 The significance of nitrification for oceanic new production. *Nature* **447**, 999–1002. (doi:10.1038/nature05885)

49. Smith CR (ed.) 2008 Biodiversity, species ranges, and gene flow in the abyssal Pacific nodule province: predicting and managing the impacts of deep seabed mining. ISA technical study no. 3, 1–38.
50. Glover AG, Smith CR, Patterson GLJ, Wilson GDF, Hawkins L, Shearer M. 2002 Polychaete species diversity in the central Pacific abyss: local and regional patterns, and relationships with productivity. *Mar. Ecol. Prog. Ser.* **240**, 157–170. (doi:10.3354/meps240157)
51. UNESCO. 2009 Global open oceans and deep seabed (GOODS): biogeographic classification. IOC technical series, 84. Paris: UNESCO-IOC.
52. Kitchingman A, Lai S. 2004 Inferences on potential seamount locations from mid-resolution bathymetric data. In *Seamounts: biodiversity and fisheries* (eds T Morato, D Pauly), pp. 7–12. Fisheries Centre, University of British Columbia.
53. Borowski C. 2001 Physically disturbed deep-sea macrofauna in the Peru Basin, southeast Pacific, revisited 7 years after the experimental impact. *Deep-Sea Res. II* **48**, 3809–3839. (doi:10.1016/S0967-0645(01)00069-8)
54. Miljutin DM, Miljutina MA, Arbizu PM, Galéron J. 2011 Deep-sea nematode assemblage has not recovered 26 years after experimental mining of polymetallic nodules (Clarion–Clipperton Fracture Zone, Tropical Eastern Pacific). *Deep-Sea Res. Part I: Oceanogr. Res. Pap.* **58**, 885–897. (doi:10.1016/j.dsr.2011.06.003)
55. White C, Halpern BS, Kappel CV. 2012 Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proc. Natl Acad. Sci. USA* **109**, 4696–4701. (doi:10.1073/pnas.1114215109)
56. Trebbico R, Halpern BS, Flemming JM, Field C, Blanchard W, Worm B. 2011 Mapping species richness and human impact drivers to inform global pelagic conservation prioritization. *Biol. Conserv.* **144**, 1758–1766. (doi:10.1016/j.biocon.2011.02.024)
57. Dunn DC, Boustany AM, Halpin PN. 2011 Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. *Fish Fish.* **12**, 110–119. (doi:10.1111/j.1467-2979.2010.00388.x)
58. Van Dover CL, Smith CR, Ardron J, Dunn D, Gjerde K, Levin L, Smith S. 2012 Designating networks of chemosynthetic ecosystem reserves in the deep sea. *Mar. Policy* **36**, 378–381. (doi:10.1016/j.marpol.2011.07.002)
59. Friedlander AM *et al.* 2011 Integration of remote sensing and in situ ecology for the design and evaluation of marine protected areas: examples from tropical and temperate ecosystems. In *Remote sensing of protected lands* (ed. YQ Wang), pp. 245–279. Boca Raton, FL: CRC Press.
60. Harris PT, Whiteway T. 2009 High seas marine protected areas: benthic environmental conservation priorities from a GIS analysis of global ocean biophysical data. *Ocean Coastal Manage.* **52**, 22–38. (doi:10.1016/j.ocecoaman.2008.09.009)
61. Clark MR, Watling L, Rowden AA, Guinotte JM, Smith CR. 2011 A global seamount classification to aid the scientific design of marine protected area networks. *Ocean Coastal Manage.* **54**, 19–36. (doi:10.1016/j.ocecoaman.2010.10.006)
62. Smith C *et al.* 2008 Rationale and recommendations for the establishment of preservation reference areas for nodule mining in the Clarion–Clipperton Zone. Fourteenth session. Kingston, Jamaica, 26 May–6 June 2008. [http://www.isa.org.jm/en/sessions/2008/documents: Legal and Technical Commission, International Seabed Authority.](http://www.isa.org.jm/en/sessions/2008/documents:Legal%20and%20Technical%20Commission,%20International%20Seabed%20Authority.2008.pdf) Technical document no. ISBA/14/LTC/2.
63. United Nations General Assembly. 2012 *The future we want*. Rio de Janeiro: United Nations General Assembly.
64. Veitch L, Dulvy NK, Koldewey H, Lieberman S, Pauly D, Roberts CM, Rogers AD, Baillie JEM. 2012 Avoiding empty ocean commitments at Rio+20. *Science* **336**, 1383–1385. (doi:10.1126/science.1223009)