Conserving pattern and process in the Southern Ocean: designing a Marine Protected Area for the Prince Edward Islands

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Abstract: South Africa is currently proclaiming a Marine Protected Area (MPA) in the Exclusive Economic Zone (EEZ) of its sub-Antarctic Prince Edward Islands. The objectives of the MPA are to: 1) contribute to a national and global representative system of MPAs, 2) serve as a scientific reference point to inform future management, 3) contribute to the recovery of the Patagonian toothfish (*Dissostichus eleginoides*), and 4) reduce the bird bycatch of the toothfish fishery, particularly of albatrosses and petrels. This study employs systematic conservation planning methods to delineate a MPA within the EEZ that will conserve biodiversity patterns and processes within sensible management boundaries, while minimizing conflict with the legal toothfish fishery. After collating all available distributional data on species, benthic habitats and ecosystem processes, we used C-Plan software to delineate a MPA with three management zones: four IUCN Category Ia reserves (13% of EEZ); two Conservation Zones (21% of EEZ); and three Category IV reserves (remainder of EEZ). Compromises between conservation target achievement and the area required by the MPA are apparent in the final reserve design. The proposed MPA boundaries are expected to change over time as new data become available and as impacts of climate change become more evident.

Introduction

There is currently an increase in appreciation of the role that Marine Protected Areas (MPAs) can play in conserving marine biodiversity, while concurrently ensuring the sustainable use of living marine resources (e.g. Gell & Roberts 2003, Gjerde & Breide 2003). International endorsements for MPAs as a management tool include policy statements issued by the World Summit on Sustainable Development (United Nations 2002) and the World Parks Congress (IUCN 2004). These statements set a target for governments to protect 20–30% of all marine habitats under their jurisdiction (i.e. including Economic Exclusive Zone) by 2012. The South African Government has publicly committed itself to these goals (e.g. Department of Environmental Affairs and Tourism 2001/2002, 2004), and has recently announced its intention to declare its largest MPA yet, within the EEZ of the sub-

Antarctic Prince Edward Islands (Nel *et al.* 2005, South Africa 2005). The position of the islands (Marion and Prince Edward) in the southern Indian Ocean (Fig. 1) also places them within the area managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), whose Scientific Committee has recently endorsed the fact that a representative network of scientifically planned MPAs would be beneficial to furthering the guiding principles of both CCAMLR (Article 2) and the 1991 Madrid Protocol on Environmental Protection to the Antarctic Treaty (CCAMLRb 2005). It therefore follows that the development of an ecologically representative and scientifically planned MPA around the Prince Edward Islands is consistent with both national policy as well as the international treaties that apply in this area.
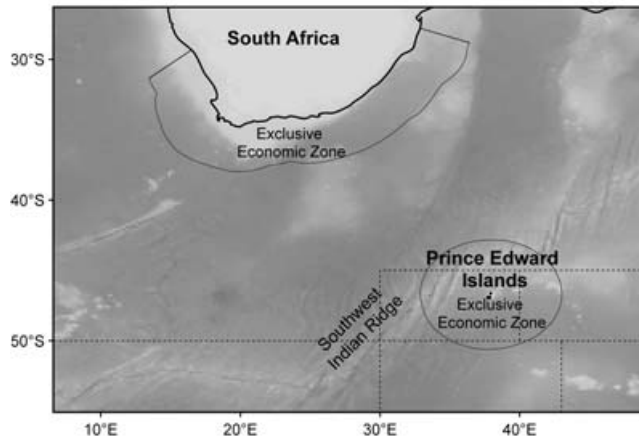
The Prince Edward Islands have been managed as a

Fig. 1. The position of the Prince Edward Islands and the EEZ in the Southern Ocean, in relation to the CCAMLR statistical areas (dashed lines).

Special Nature Reserve since November 1995 (PEIMPWG 1996), but no marine component is included. To reduce the incidental mortality of procellariiform seabirds by longline fishing (Nel *et al.* 2002b, 2002c, 2003), however, no fishing activities have been permitted within the 12 nautical mile territorial waters since December 2004. Additionally, fishing activities by South African vessels in waters surrounding the islands in the main abide by the CCAMLR regulations and guidelines. The announcement of the South African Government in July 2004 of its intention to proclaim a major new MPA in the waters around the Prince Edward Islands (and not just the territorial waters) is proof of its national commitment to combat Illegal, Unreported and Unregulated (IUU) fishing in the Southern Ocean. This commitment is further supported by the purchase of new environmental patrol vessels, and ongoing bilateral negotiations aimed at enhancing international Monitoring, Control and Surveillance co-operation within the Southern Ocean.

A MPA around the Prince Edward Islands would fulfil four major objectives:

1. contribute to a national and global representative system of Marine Protected Areas, by providing protection for unique species, habitats and ecosystem processes (e.g. foraging grounds, shelf areas with increased nutrients, etc.),

2. serve as a scientific reference point that can inform the future management of the area,

3. contribute to the recovery of the Patagonian toothfish *Dissostichus eleginoides*, which has been so over-exploited that its spawning biomass may be only a few percent of pre-exploitation levels just ten years ago (Brandão *et al.* 2002), and

4. aim to reduce the bycatch of the toothfish fishery, particularly of albatrosses and petrels (Nel & Nel 1999,

Nel *et al.* 2002c) since the islands support 44% and 10% of the global populations of the wandering and grey-headed albatrosses, respectively (Crawford & Cooper 2003).

More specific motivation for a large (inshore and offshore) MPA around the Prince Edward Islands includes the following:

- The uniqueness, pristine nature and high level of endemism of the islands themselves (Chown *et al.* 1998). In an assessment of the status of Southern Ocean islands, Chown *et al.* (2001) demonstrated that Prince Edward Island is one of the most pristine islands, emphasizing the need to limit future human intervention as far as possible. South Africa has recently nominated the islands and their territorial waters as a World Heritage Site (Fischer *et al.* 2006).

- Protection of the relationship between the marine and terrestrial environments, especially of the nutrient cycle driven by birds and seals (Froneman & McQuaid in press, Smith & Froneman in press). Protection of the terrestrial environment is thus reliant on a healthy marine environment.

- The foraging requirements of the top predators. Many bird and seal species breed on the islands (e.g. Hofmeyr & Bester 1997, Pistorius *et al.* 1999, Crawford & Cooper 2003), and forage either close to the islands (inshore feeders), or within and beyond the greater EEZ (offshore feeders). The birds especially are affected both indirectly (competition for resources), and directly (as bycatch), by fishing activities in the area. Many of these bird species are globally threatened (Crawford & Cooper 2003).

- The islands are showing rapid change in step with global climate change (Pakhomov & Chown 2003). Any anthropogenic reduction in the resilience of species that breed on the islands or forage within the EEZ may render these species locally extinct, for example, if sea surface temperatures change drastically (Mélice *et al.* 2003), or if the position of the oceanic fronts moves farther south (Lutjeharms *et al.* 2002). There is evidence that many birds and seals forage in the vicinity of these fronts (Jonker & Bester 1998, Nel *et al.* 2001).

- The precautionary principle. Benthic surveys have been conducted only on the shelf between the two islands (Beckley & Branch 1992, Branch *et al.* 1993), and very little is known about the benthic habitats within the EEZ. Undescribed species, as well as major geological features (such as hydrothermal vents on the Southwest Indian Ridge), are all likely to occur within the EEZ. Given that there is potential for oil and gas exploration in the area as well as an interest in tourism

(especially if World Heritage Status is obtained), representative habitats need to be set aside to mitigate future threats.

- A number of shipping-related processes threaten the marine (and therefore terrestrial) environments. These include the introduction of alien species, via ballast water or on hulls (Frenot *et al.* 2005), pollution such as from oil spills (Cooper & Condy 1988), and the discarding of fishery-related gear leading to harmful effects on both seals and birds (Nel & Nel 1999, Hofmeyr *et al.* 2002). At present fishing vessels use the lee of the island to shelter from storms.

- A South African MPA within its sub-Antarctic EEZ will match and complement the two Marine Parks (equivalent to MPAs) recently declared by Australia in the EEZs of its sub-Antarctic island groups: Macquarie, and Heard and McDonald (Environment Australia 2001, 2005), thus contributing to a developing network of MPAs both within the Southern Ocean and globally. This network will also represent a west–east gradient in oceanographic biogeography and will lend support to ongoing efforts by international bodies such as the Antarctic Treaty through its Committee on Environmental Protection, CCAMLR and the World Conservation Union (IUCN) (e.g. Kelleher 1999, Gjerde & Breide 2003, ATCM 2005, CCAMLR 2005a, 2005b).

Our aim has been to meet the four objectives listed previously by designing a MPA for the Prince Edward Islands EEZ that will: 1) conserve representative areas of biodiversity patterns (species and ecosystems) while simultaneously conserving biodiversity processes (e.g. foraging grounds, nutrient cycles), 2) avoid conflict with the fishing industry where possible, and 3) have sensible marine management boundaries. The study followed a systematic conservation planning approach (see Margules & Pressey 2000) that collated all available information on biodiversity patterns and processes. Despite the previous extensive scientific research (Hänel & Chown 1999, Chown & Froneman in press), continuous spatial information that covers the entire EEZ is limited, and a number of different organizations and institutions maintain existing datasets. In addition to providing a central location within the appropriate Government agency for all existing data, our study also forms a spatial planning framework for future developments of MPA design.

Methods

Study area

The EEZ of the Prince Edward Islands covers 528 020 km^2 and lies in the Southern Ocean between approximately 42°45'–50°45'S, and 32°45'–43°E (Fig. 1). It includes four
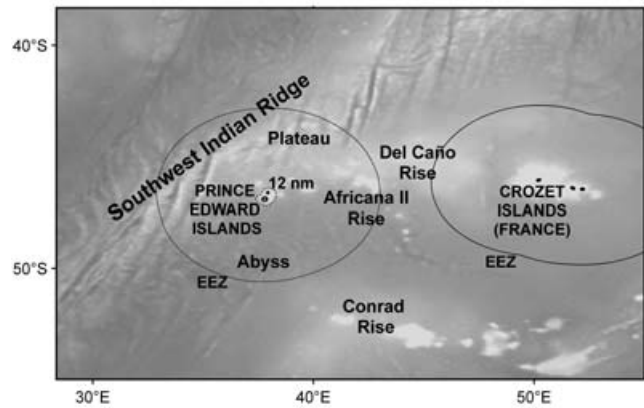

Fig. 2. Bathymetry of the Prince Edward Islands EEZ, with the Iles Crozet shown to the east. The four broad habitats within the EEZ include the Southwest Indian Ridge in the west, the plateau area in the northern half (mostly shallower than 3500 m), the abyss in the southern half (deeper than 3500 m), and the islands themselves. The territorial seas are shown at 12 nautical miles.

broad habitats: the Southwest Indian Ridge in the northwest; a plateau area with seamounts and rises in the northern half; an abyssal area in the southern half; and the islands and the shallow waters between them in the centre (Fig. 2). The two islands, Marion and Prince Edward, lying approximately at 46°45'S and 37°45'E, have a combined terrestrial area of 339 km^2. The Sub-Antarctic Front (SAF) lies to the north of the islands, and the Antarctic Polar Front (APF) lies to the south (Lutjeharms 1985). The southern SAF (SSAF) lies between the SAF and the APF. Consequently, three major water masses occur within the EEZ: sub-Antarctic surface waters (north of the SAF); northern polar frontal waters (between the SAF and the SSAF); and southern polar frontal waters (between the SSAF and the APF) (Ansorge & Lutjeharms 2002).

The eastern border of the EEZ falls on the Africana II Rise, which itself forms part of the much larger Del Caño Rise, to the east of which lie France's Iles Crozet (Fig. 2). The Prince Edward and Crozet islands lie 1050 km apart, with *c.* 310 km separating their respective EEZs.

Summary of the base data

Our initial task was to collate and standardize all existing spatial datasets for the EEZ, as well as to generate new spatial data from existing data or from interviews with experts. Consultative workshops with stakeholders and an extensive literature survey completed the data-acquisition phase. All data are now housed within the implementation agency (Marine and Coastal Management Branch, Department of Environmental Affairs and Tourism), and are stored in Geographic Information Systems (GIS) format (ArcView 3.2 and ArcInfo 7, ESRI 1998). Those datasets that did not cover the entire EEZ were excluded from the systematic conservation planning process. Table I

Table I. Datasets used in the systematic conservation planning of a marine protected area for the EEZ of the Prince Edward Islands in the Southern Ocean.

Dataset		Data source	Used in the plan
Biodiversity patterns (species):	Invertebrates	Trawl data from MCM[1]	No[2]
	Fish	Gon & Heemstra (1990)	Yes
	Cetaceans	M.N. Bester & P.B. Best[3] (personal communication 2005)	No[2]
Biodiversity patterns (habitats):	Bathymetry (2 minute)	NOAA (2001a)	Yes
	Sediment thickness	NOAA (2001b)	Yes
	Benthic habitats	Derived from bathymetry and sediment thickness	Yes
	Seamounts	Derived from Bathymetry	Yes
Fixed processes (fine scale):	Coastal processes	1 km coastal buffer generated in GIS from island coastlines	Yes
	Island shelf processes	Derived from bathymetry (500 m isobath)	Yes
	Productive island areas	Derived from bathymetry (1800 m isobath)	Yes
	Inshore foraging areas	40 km buffer generated in GIS from island coastlines	Yes
Flexible processes (broad scale):	Seabird foraging areas	BirdLife International (2004)	Yes[4]
	Elephant seal foraging areas	M.N. Bester & C.A. Tosh	Yes
	Average position of the fronts	Reproduced with kind permission from I.J. Ansorge[5]	Yes
Fishing activities:	Fishing effort	MCM–CCAMLR[6] Scientific Observer Logbook data	Yes
	Bird bycatch	Nel *et al.* (2002a)	Yes
Management boundaries:	Island outlines	K.I. Meiklejohn[7]	Yes
	EEZ (200 nm)	1:10 000 000 SAN[8] charts	Yes

[1]Marine and Coastal Management (Department of Environment Affairs and Tourism), [2]Data available for only limited parts of the EEZ (R.W. Leslie)
[3]Mammal Research Institute, University of Pretoria, [4]Only data for birds tracked from the Prince Edward Islands were used (i.e. grey-headed and wandering albatrosses), [5]Hydrographic data used for this study were collected during the MOES, MIOS and DEIMEC programmes funded through the South African National Antarctic Programme (Department of Environmental Affairs and Tourism), [6]Commission for the Conservation of Antarctic Marine Living Resources
[7]Department of Geography, Geoinformatics & Meteorology, University of Pretoria, [8]South African Navy, Hydrographic Office

summarizes the data collated and developed for the study.

Biodiversity patterns (species)

A database of the fish occurring in the Prince Edward Islands EEZ was compiled using distribution and habitat data from Gon & Heemstra (1990). A subset of 19 of these species was extracted for analyses. The subset contained all species from the family Nototheniidae (this is the largest sub-Antarctic family), as well as possible endemics, threatened species, and any species linked to benthic (as opposed to pelagic) habitats (Table II). Quantitative depth-range data from Gon & Heemstra (1990) and two-minute bathymetry data were used to create two-minute GIS maps

Table II. The subset of 19 fish species used in the conservation planning analyses for the Prince Edward Islands.

Family	Species	Rationale for inclusion
Halosauridae	*Halosaurus macrochir* Günther	Benthic
Synaphobranchidae	*Diastobranchus capensis* Barnard	Benthic
Muraenolepididae	*Muraenolepis marmoratus* Günther	Benthic
Muraenolepididae	*Muraenolepis orangiensis* Vaillant	Benthic
Moridae	*Guttigadus kongi* Markle & Melendez	Benthopelagic
Macrouridae	*Coryphaenoides filicauda* Günther	Benthic
Macrouridae	*Macrourus carinatus* Günther	Benthic
Congiopodidae	*Zanclorhynchus spinifer* (Günther)	Benthic
Zoarcidae	*Lycodapus antarcticus* Tomo	Meso- to bathypelagic[1]
Nototheniidae	*Dissostichus eleginoides* Norman	Benthic to benthopelagic, heavily exploited
Nototheniidae	*Gobionotothen marionensis* Günther	Benthic, may be endemic to the islands
Nototheniidae	*Lepidonothen larseni* Lonnberg	Benthic, ecologically important[2]
Nototheniidae	*Lepidonotothen squamifrons* Günther	Benthic, commercially exploited and may be threatened
Nototheniidae	*Notothenia coriiceps* Richardson	Benthic, ecologically important
Nototheniidae	*Notothenia rossii* Richardson	Benthic, rare
Nototheniidae	*Paranotothenia magellanica* Forster	Benthic, ecologically important
Harpagiferidae	*Harpagifer georgianus* Nybelin	Benthic, probably endemic to the Prince Edward Islands and South Georgia
Channichthyidae	*Channichthys rhinoceratus* Richardson	Benthic
Achiropsettidae	*Mancopsetta milfordi* Penrith	Benthic

[1]All specimens to date are from bottom trawls, but the species is associated with seamounts hence its inclusion
[2]Fulfils a key role in the food web

of predicted habitat ranges for each species, within the EEZ. These GIS maps were overlaid to produce a final species richness layer. Only two-minute cells with more than four potential species were targeted in the conservation planning analyses. The maximum species richness of any one cell was 13.

Biodiversity patterns (habitats)

In addition to the four broad habitats within the EEZ (Fig. 2), a higher resolution map of benthic habitats was delineated. Owing to a lack of regional-scale data on bathymetry, the ETOPO (two-minute) global gridded data (NOAA 2001a) were used. Within this dataset, seafloor data for the EEZ were derived from satellite altimetry observations combined with quality-assured shipboard echo-sounding measurements (Smith & Sandwell 1997).

To produce a map of unsampled benthic habitats for the entire EEZ, we combined bathymetry data with a map of sediment thickness (five-minute, NOAA 2001b), and produced a surrogate benthic habitat map for use in the conservation planning analyses. Bathymetry and sediment thickness were the only two biophysical variables for which complete coverage of the EEZ was available. Habitat classes in the final map were derived by dividing the bathymetry map into five biologically meaningful classes: 0 to -200 m (island shelf), -200 to -500 m (shelf of mounts and rises), -500 to -1800 m (upper slope), -1800 to -3500 m (lower slope) and < -3500 m (abyss) (Lombard *et al.* 2004). For consistency, the sediment map was similarly divided into five classes of thickness using a natural breaks (Jenks) classification method. Values ranged from 13 to 1021 m. Spatial intersections of these two classified maps produced a final map of 21 different combinations of classes (four combinations did not exist). We treated these 21 combinations as benthic habitat surrogates, but recognize that no benthic data are currently available to test them for validity. The islands themselves were classified as one of the 21 habitats.

Owing to the increased biodiversity and productivity associated with seamounts and their vulnerability to fishery impacts (Rogers 1994, Roberts 2002), we produced a map of seamounts and rises, using the 800 m isobath as a cut off. Eleven seamounts and rises occur in the northern half of the EEZ.

Biodiversity processes

To delineate spatial surrogates for biodiversity processes, an understanding of the spatial and temporal variability of the major processes within the study area is required. These processes operate at a variety of scales, which should be recognized in MPA design.

Like other small oceanic islands, nutrient input to the Prince Edward Islands is primarily from the surrounding ocean (Smith 1978, 1987). Top predators (birds and seals), which use the islands to breed and moult, bring nutrients to the islands from two main sources: the islands' shelf area, and the pelagic environment (both within and outside the EEZ). Island run-off, driven by rainfall, then augments the nutrients in shelf waters. This close interaction between the marine and terrestrial environments is referred to as the islands' life support system (LSS), which has two components (Pakhomov & Chown 2003).

Component one (the retention system) operates inshore and dominates when the SAF lies far to the north of the islands (Perissinotto & Duncombe Rae 1990). Water is retained on the shallow island shelf, and increased macronutrient concentrations and water column stability generate phytoplankton blooms (the island mass effect, Allanson *et al.* 1985). Phytoplankton blooms then provide carbon to the benthos, which in turn provide food for the swimming shrimp, *Nauticaris marionis* Bate. This shrimp is an important component in the diet of a variety of inshore-foraging seabirds (Perissinotto & McQuaid 1990, Pakhomov *et al.* 1999), and couples the pelagic environment to the islands' benthic environment (Perissinotto & McQuaid 1990).

Component two operates offshore and dominates when the SAF is close to the islands. Two major food-supply mechanisms have been proposed for this component (Pakhomov & Chown 2003). The first is a replenishing and pulsing mechanism that operates when flow-through regimes dominate between the islands (Perissinotto *et al.* 2000). Water is not trapped between the islands, and the Antarctic Circumpolar Current (ACC) advects zooplankton and nekton towards the islands, from west to east (Pakhomov & Froneman 1999a). This food source is subsequently trapped by the shallow island shelf and is depleted by island predators during the daytime, but stocks are replenished at night by advection from upstream, when the predators are inactive (the replenishing hypothesis) (Perissinotto & McQuaid 1992).

The second mechanism is associated with frontal movements and the formation of mesoscale eddies that are created as the ACC crosses the Southwest Indian Ridge (Ansorge & Lutjeharms 2005). Elevated plankton and fish biomass are associated with the two major frontal systems (the SAF and the APF) in the vicinity of the islands (Pakhomov & Froneman 2000). Although only the pelagic feeders from the islands (e.g. king penguins *Aptenodytes patagonicus* Miller and southern elephant seals *Mirounga leonina* L.) are able to travel to these fronts to forage (Bost *et al.* 1997, Jonker & Bester 1998), the advection of these food sources to the islands can make them available to the more inshore foragers (Pakhomov & Froneman 1999b). There is also evidence that mesoscale eddies created upstream of the islands are important feeding grounds for top predators (Hofmeyr & Bester 1997, Klages & Bester 1998, Pistorius *et al.* 1999, Nel *et al.* 2001).

In order to capture these processes in a MPA design, we divided them into those that are fine scale and spatially fixed, and those that are broad scale and spatially flexible (variable).

Fixed processes

We defined a one-kilometre buffer around the islands as the coastal inshore zone (Coastal processes in Table I). This zone incorporates the dense stands of *Macrocystis laevis* Hay, an endemic kelp on the eastern coast of Marion Island approximately 100 m offshore in 5–20 m of water (Beckley & Branch 1992). The kelp beds are areas of high biodiversity and add to ecosystem diversity on the shelf by providing important habitat for invertebrates (Pakhomov *et al.* 2002), and by trapping fresh water run-off from the islands, thereby reducing salinity and potentially promoting phytoplankton blooms (Pakhomov & Froneman 1999b). This buffer also covers the foraging grounds of the Crozet cormorant *Phalacrocorax [atriceps] melanogenis* (Blyth), kelp gull *Larus dominicanus* Lichtenstein, the Kerguelen tern *Sterna virgata* Cabanis and Antarctic tern *S. vittata* Gmelin (Crawford & Cooper 2003).

To capture the shelf-related processes of the inshore LSS, we chose the 500 m isobath around the islands (Island shelf processes in Table I). This incorporates the shelf areas of both islands as well as the area between them. The shelf supports a diverse and rich biomass of benthos (Gon & Mostert 1992, Branch *et al.* 1993) and sustains a food web on which inshore-foraging seabirds rely. Concern has been raised because populations of inshore-foraging species (the Crozet cormorant, the gentoo penguin *Pygoscelis papua* Forster, and the rockhopper penguin *Eudyptes chrysocome* Forster) have decreased in recent years (Crawford *et al.* 1998, Crawford & Cooper 2003).

Whereas these first two processes have benthic components, the third fixed process is of a pelagic nature and attempts to capture the "island mass effect" of increased Chl *a* concentrations that are observed periodically in the downstream region of the islands. It was delineated with the 1800 m isobath around the islands (i.e. the upper/lower slope division). This area captures elevated Chl *a* and myctophid fish concentrations around the islands, as well as a downstream area of high zooplankton biomass (Pakhomov & Froneman 1999a, 2000, Ansorge & Lutjeharms 2002) (Productive island areas in Table I). It may also be a nursery area for Patagonian toothfish (R.W. Leslie personal communcation 2005).

Although gentoo and rockhopper penguins are usually described as inshore feeders, their foraging ranges extend off the shelf to average distances of 29 km and 33 km, respectively (Brown 1987, Wilson *et al.* 1989). To capture this and the phytoplankton blooms we buffered the islands by a distance of 40 km (Inshore foraging areas in Table I). This buffer also incorporates all territorial waters (12 nm =

22.224 km).

Flexible processes

A flexible process is an oceanographic or biological process that is not fixed in space, although its spatial occurrence may be predictable to varying degrees. Although flexible processes have formed part of terrestrial conservation plans in South Africa for some years (e.g. Cowling *et al.* 1999, 2003, Balmford 2003), their integration into MPA planning is still comparatively undeveloped. For the present study, we defined and mapped three flexible processes, namely foraging areas for wandering and grey-headed albatrosses (*Diomedea exulans* L. and *Thalassarche chrysostoma*, Forster, respectively); foraging areas for southern elephant seals; and the average positions of the SAF and the APF. These are all broad-scale, spatially variable processes that operate offshore, and the nutrient input contribution made by offshore foragers into the islands is by far the most significant (Pakhomov & Froneman 1999b).

The Prince Edward Islands support 44% and 10% of the global populations of the wandering and grey-headed albatrosses, respectively. Both species are classified as Vulnerable, primarily as a result of population reductions since the 1980s (BirdLife International 2004), attributed mainly to mortality associated with longline fishing for tuna (*Thunnus* spp.) and Patagonian toothfish (Nel *et al.* 2002b, 2002c, 2003). During 1997–1998, breeding wandering and grey-headed albatrosses were tracked by satellite from Marion Island (Nel *et al.* 2000, 2001, 2002a). For the present study, habitat utilization was calculated using kernel density estimators from the Animal Movement formula developed by Hooge & Eichenlaub (1997). Kernel density distribution maps were produced for each species using the same parameters used by the BirdLife International (2004) study. Maps show contours of 50%, 51–75%, and 76–95% levels of habitat utilization. These contours represent the minimum polygon of densely clustered points that include a specified percent of the satellite points. Consequently, the 50% kernel represents the densest clustering of 50% of the points recorded and highlights areas of maximum utilization.

To combine the habitat utilization maps from both bird species, we scored the 50% habitat utilization polygons with a three, and the 51–75%, and 76–95% polygons with twos and ones, respectively. We overlaid the polygon maps, and summed the scores, thereby generating polygons with values ranging from six (maximum usage by both species) to one (used minimally by only one species).

Steady declines in numbers of southern elephant seals have been reported for the Prince Edward Islands for the last fifteen years (Pistorius *et al.* 1999, Bester & Hofmeyr 2005, McMahon *et al.* 2005), although, the Marion Island population now seems to be stabilizing (Pistorius *et al.* 2004). Causes for these declines are not clearly understood

(McMahon *et al.* 2005). For the present study, 48 satellite tracks for Marion Island southern elephant seals were analysed (Pangaea 2005). Outliers were removed, and habitat utilization maps were produced with the same methods used for the seabirds. Data from the seals were combined with the albatross data with the same scoring method generating polygons with values ranging from nine (maximum usage by all three species) to one (used minimally by only one species).

Given the important role played by the two oceanic fronts (the SAF and the APF) in maintaining the LSS of the Prince Edward Islands, we attempted to calculate their average positions within the EEZ, using sub-surface (200 m depth) temperature data (I.J. Ansorge unpublished data). Data from 771 points collected from cruises over eight years (between 1989 and 2005) were converted to raster grids and contoured. The position of the APF occurs at the 2°C contour, whereas the SAF can be split into a northern (SAF) and southern front (SSAF), lying at the 6°C and 3.5°C contours, respectively (Froneman *et al*. 2002). These three fronts were extracted from the data for each of the eight years. Unfortunately the entire EEZ was not surveyed in all years, nor was there consistency in the area surveyed. Consequently, our maps of average frontal positions are incomplete and should be considered preliminary. Our contours, however, do fall within the described range of these frontal movements, which have a large spatial variation globally (Froneman *et al.* 2002, Lutjeharms *et al.* 2002).

Fishing activities

Demersal longline fishing for Patagonian toothfish is currently the main non-research-related human activity in the Prince Edward Islands' EEZ (low-impact tourism exists in the form of passing yachts). Sanctioned fishing in the EEZ began in October 1996, after considerable poaching by IUU vessels earlier in the year (Nel *et al*. 2002c). Since 1996, all legal South African fishing vessels operating in the EEZ have been required to carry CCAMLR Scientific Observers and their reports contain information on the fishing activities in the region from 1996 to the present day (2005). Data were extracted from these reports to map fishing localities. We chose a single point (the line setting start point) to represent the location of each longline set by each vessel. The spatial distribution of fishing effort and catch data are summarized in Lombard (2006).

Study area outlines

Coastlines for Marion and Prince Edward Island were provided by K.I. Meiklejohn (University of Pretoria) and were derived from 2000 Landsat imagery. Territorial and jurisdictional zones (for example, the EEZ) were digitised from the South African Navy Maritimes Zones chart SAN MZ 1 (1:10 000 000, Hydrographic Office, S.A. Navy, published in 1995).

Systematic conservation planning

During the past two decades, the field of systematic conservation planning (Margules & Pressey 2000), has developed rapidly. Systematic planning is based on the need to conserve a representative sample of a region's biodiversity and to ensure its persistence through the exclusion of threatening processes and the inclusion of ecological and evolutionary processes that maintain and generate biodiversity (Cowling *et al.* 2003).

A systematic conservation plan relies on the definition of conservation targets (quantitative expressions of a region's conservation goals), which define how much of each biodiversity pattern (e.g. habitat types or species), and which biodiversity processes (e.g. foraging areas), should be included within the protected area boundaries. Once biodiversity patterns and processes have been spatially delineated, the study area is subdivided into planning units

Table III. Targets for the systematic conservation planning of a marine protected area for the EEZ of the Prince Edward Islands.

Biodiversity patterns and processes		Target
Biodiversity patterns (species):	Fish	All 2 minute cells with four to 13 species[1]
Biodiversity patterns (habitats):	Broad-scale habitats	MPA to represent each of the four broad-scale habitats
	Major water masses	MPA to represent each of the three major water masses
	Benthic habitats	20% of the area of each of 20 habitats, and all of the Land habitat
	Seamounts	All of the 11 seamounts and rises
Fixed processes:	Coastal processes	Entire area of 1 km coastal buffer
	Island shelf processes	Entire area of inshore island shelf
	Productive island areas	Entire area of productive island areas
	Inshore foraging areas	Entire area of 40 km buffer
Flexible processes:	Sea bird and elephant seal foraging areas	MPA to incorporate major movement axes as shown by the combined bird and seal habitat utilization data, as well as all values from eight to nine (see Fig. 6c)
	Average position of the fronts	MPA to incorporate average positions of the SAF, SSAF and APF (see Fig. 6c).

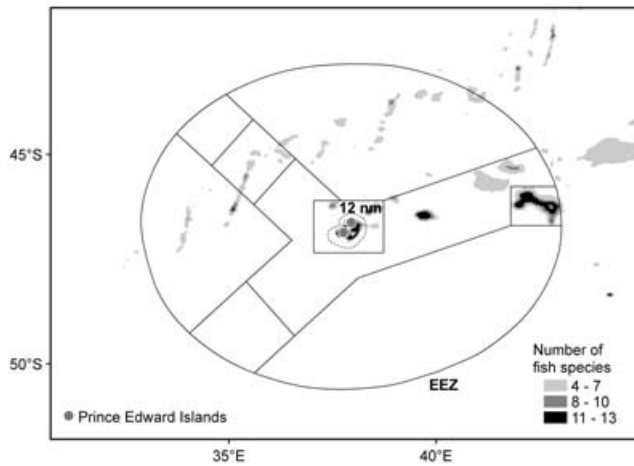[1] Areas with one to three species covered too much of the EEZ to serve as practical targets

Fig. 3. Species richness of a subset of 19 fish species in the Prince Edward Islands EEZ (see Table II). Only two-minute grid cells with ≥ four species are shown, overlaid on the proposed MPA boundaries (see Fig. 7).

(typically grid squares or hexagons). The contribution of each planning unit to the quantitative targets is then calculated, and an efficient and practical spatial arrangement of planning units is then identified to meet all the targets. Various software systems are available to perform these calculations, for example C-Plan and MARXAN (Pressey 1999, Ball & Possingham 2000, Possingham *et al.* 2000).

Targets defined for the present study are listed in Table III. The EEZ was divided into 9839 grid cells or planning units of 4 x 4 nautical miles, and the contribution of each of these units to the targets was calculated with C-Plan software (Pressey 1999). C-Plan calculates the irreplaceability value of each planning unit - where irreplaceability is a value (from 0–1) of the likelihood that the planning unit will be needed to meet targets (Pressey 1999, Ferrier *et al.* 2000).

Design rules

To maximize effective implementation of a planning design, protected area planning should always be conducted within an implementation framework (Pierce *et al.* 2005, Knight *et al.* 2006). We identified three primary factors that would facilitate implementation of our recommended MPA boundaries: the final area of the MPA, the overlap of the MPA with current legal fishing activities, and the complexity of the boundaries. Consequently, we constrained our planning design by the following four rules:

1. Minimize the area required to meet targets,
2. Avoid current legal fishing activities where choices exist, but do not compromise biodiversity targets,
3. Keep the boundaries of the MPA as straight lines, joining points that are on exact degrees and minutes, and
4. Exclude all planning units that are only partially within the EEZ (i.e. on the boundary, $n = 438$).

Analyses

Our MPA design proceeded in three steps using C-Plan.

In Step 1 we identified four zones as equivalent to Strict Nature Reserves (IUCN Category Ia). Each of these was representative of one of the four broad-scale habitats, and
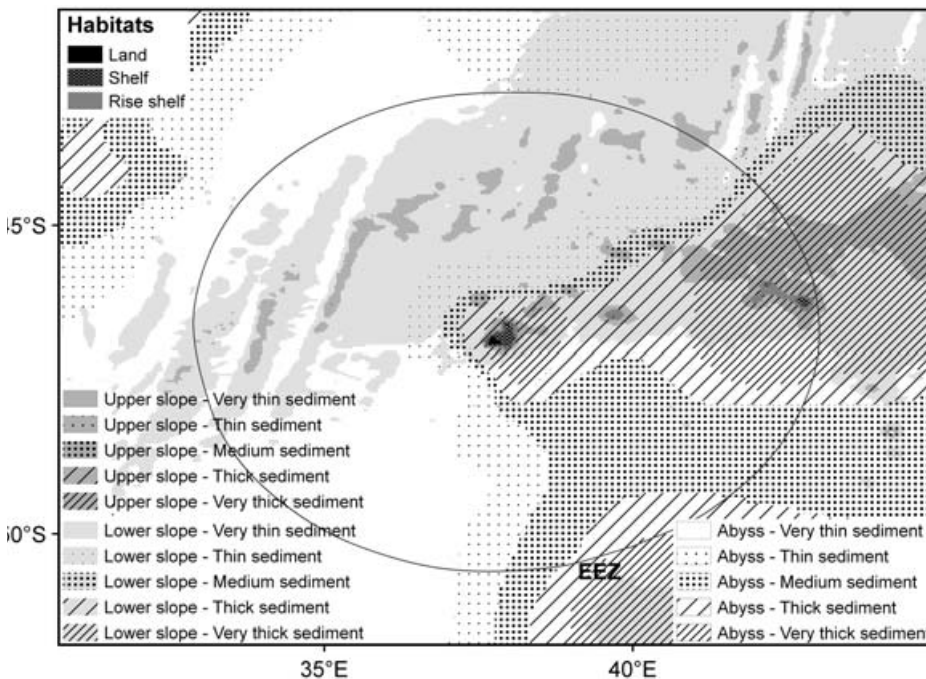

Fig. 4. Benthic habitats defined for the EEZ, using combinations of bathymetry and sediment thickness classes. The habitats labelled Shelf and Rise shelf are actually combinations of two Shelf habitats and three Rise shelf habitats, respectively, but these have been combined into single shades for this figure, owing to their very small areas within the EEZ.

Table IV. Biodiversity patterns and processes represented within the four IUCN Category Ia reserves proposed for the Prince Edward Islands MPA (see Fig. 7).

Biodiversity patterns and processes	Southwest Indian Ridge	Prince Edward Islands	Africana II Rise	Abyss
Biodiversity patterns (species):				
Fish	8% of target area. NE boundary of reserve informed by these data and bird bycatch data[1].	All the target areas on the 3 mounts (northern and eastern boundaries of reserve were set to these).	All the target areas on the Rise (all 4 reserve boundaries were set to these).	n/a
Biodiversity patterns (habitats):				
Broad scale habitats	SW Indian Ridge and Prince Edward fracture zone[2]. NE boundary of reserve was set to capture a whole trench	The two islands (Marion and Prince Edward), and their shelf habitats.	Plateau (area shallower than 3500 m).	Abyss (area deeper than 3500 m).
Major water masses	Sub-Antarctic surface waters (i.e. north of the SAF[3]).	Northern polar frontal zone waters (between the SAF and the SSAF[3]).	Northern polar frontal zone waters (between the SAF and the SSAF).	Southern polar frontal zone waters (between the SSAF and the APF[3]).
Benthic habitats	The four reserves combined meet targets for 6 of the 21 habitats			
Seamounts	One	Three (the islands plus another two).	One[4]	n/a
Fixed processes:				
Coastal processes	n/a	Entire target	n/a	n/a
Island shelf processes	n/a	Entire target	n/a	n/a
Productive island areas	n/a	Entire target	n/a	n/a
Inshore foraging areas	n/a	Entire target[5] (southern and western boundaries were defined by this polygon).	n/a	n/a
Flexible processes:				
Bird and seal foraging areas	The NW movement axis of the combined bird and seal habitat utilization data, as well as a core area with values from 8–9 (see Fig. 6c).	All 3 species feed within this zone.	The eastern movement axis[6] of the bird habitat utilization data, which links to the Iles Crozet (see Fig. 6c).	The SW movement axis of the combined bird and seal habitat utilization data (see Fig. 6c).
Average position of the fronts	SW boundary set to incorporate the SAF[7].			Southern boundary is set by the EEZ (where APF comes closest to the EEZ), and northern boundary by the SSAF.

[1] CCAMLR Scientific Observer reports, [2] Area likely to contain active volcanoes and hydrothermal vents (I. McLachlan, Petroleum Agency South Africa, personal communication 2005). Sperm whales may utilize the deep canyons (M. Meyer, personal communication 2005). [3] SAF (sub-Antarctic Front), SSAF (southern sub-Antarctic Front), APF (Antarctic polar Front). [4] This area may be a replenishment zone for many fish species (R.W. Leslie, personal communication 2005). [5] This zone also incorporates all territorial waters. Also many whale species (M. Meyer, personal communication 2005). All bird bycatch data for the area also included in boundaries. [6] This axis is also used by many seabirds from the Crozets (BirdLife International 2004). [7] The average

the three water bodies, and was also delineated to achieve as many of the targets in the targets table as possible. Boundary lines were straight, and connected points on exact degrees and minutes (i.e. no seconds). Areas of more recent legal fishing activity were avoided where possible (i.e. where choices existed between planning units that contributed equally to targets). Table IV describes each reserve, and the rationale behind its boundaries. One of these four reserves (around the islands) met all four fixed process targets (Table III).

In Step 2, we connected the four reserves from Step 1 with straight lines, to incorporate the three movement axes defined by the highest values of the bird and elephant seal habitat utilization data. Again, we attempted to avoid areas of more recent fishing activity where choices existed. Because the Category Ia reserves were placed in areas that

also maximized targets for frontal zone average positions (Table IV), the axes also incorporated the areas of variability of the frontal positions. Areas within these axes were defined as Conservation Zones and were not given an IUCN category because their exact management status is still under consideration. Together with the Category Ia reserves, the Conservation Zones met all the flexible process targets.

At this point, the only targets that were not met by Steps 1 and 2 were those for fish, benthic habitats, and seamounts (Table III). In Step 3, we assigned all planning units that had > 90% of their areas within the proposed Step 1 and 2 reserves to the "reserved" status within C-Plan. We then calculated the contribution of all remaining planning units to meeting outstanding targets. The planning units identified by Step 3, along with the proposed Category Ia reserves and
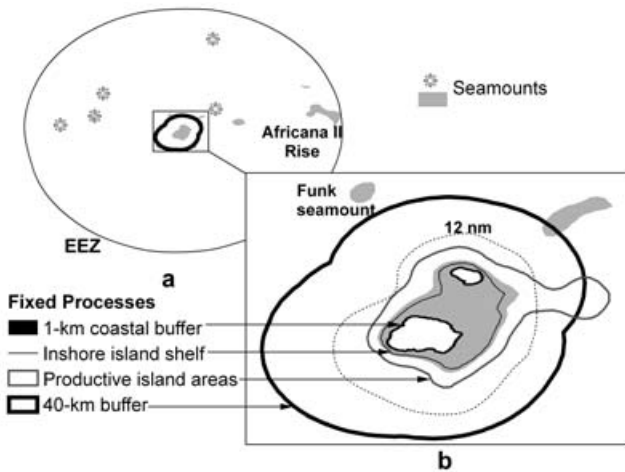
Fig. 5. a. The 11 seamounts (and rises) defined within the EEZ. The scale of the figure precludes the shading of the five smaller seamounts, which are shown as symbols (*). **b.** corresponds to the boundaries of the proposed Prince Edward Island Category Ia reserve (see Fig. 7), and also shows the four fixed processes.

Conservation Zones, met all the benthic habitat targets. However, Step 3 violated design rules one to three, and still did not meet all fish species richness and seamount targets.

Results

Biodiversity patterns (species)

Species richness of the 19 fish species, calculated per two-minute cell, is shown in Fig. 3. Areas with ≥ four species are restricted to the shallower, northern half of the EEZ, and areas of highest richness are concentrated on the shelves of the islands, seamounts, and the tops of the Southwest Indian Ridge.

Biodiversity patterns (habitats)

The 21 habitat surrogates defined for the EEZ are shown in Fig. 4. Only two habitats make up just under half of the EEZ: abyss with very thin sediments in the south west (24% of EEZ), and lower slopes with very thin sediments in the northern half (25%). The Southwest Indian Ridge dominates the western areas, and shallower habitats (islands, island shelf, seamounts, rises and their shelves) are limited to the northern half of the EEZ, particularly on a west–east axis that joins the islands to Africana II Rise. Nine of 21 habitats contribute <1% to the EEZ's total area (these are all upper slope and shallower habitats).

Figure 5 shows the distribution of the 11 seamounts and rises defined for this study. Many are well known fishing grounds for the Patagonian toothfish (R.W. Leslie personal communication 2005).
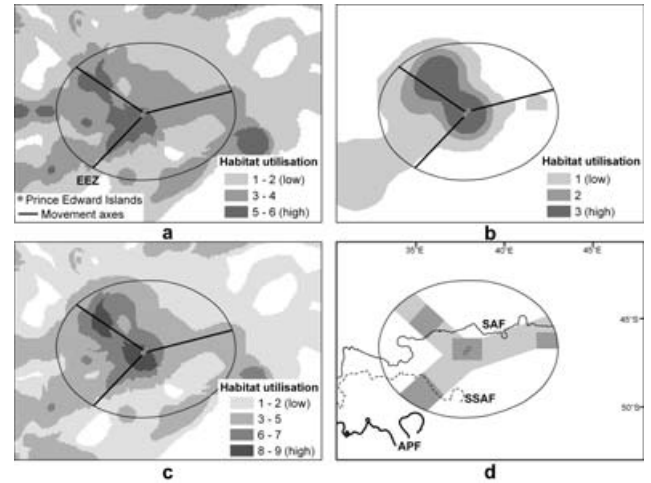

Fig. 6. Habitat utilization maps for **a.** tracked wandering and grey-headed albatrosses, and **b.** southern elephant seals. Combined habitat utilization map are sown in **c.** for both albatross species and elephant seals. Foraging movement axes are plotted in each map. **d.** shows the average position of the major oceanic fronts (SAF, SSAF and APF), overlaid on the proposed MPA boundaries (see Fig. 7).

Fixed processes

The four fixed processes are illustrated in Fig. 5b. All are associated with the islands themselves, and the 40 km buffer incorporates the other three processes, except for a small portion of the productive island areas process in the east.

Flexible processes

Habitat utilization maps for albatrosses and seals, tracked from Marion Island, show foraging patterns concentrated
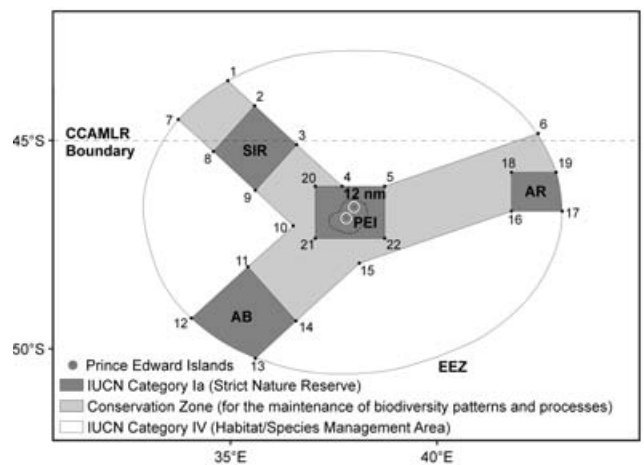

Fig. 7. The proposed boundaries for the Prince Edward Islands MPA. The four Category Ia reserves are: Southwest Indian Ridge (SIR), Prince Edward Islands (PEI), Africana II Rise (AR), and Abyss (AB) (see also Table IV). The CCAMLR Convention Area lies to the south of the CCAMLR boundary.

Table V. Areas and EEZ percentages of the reserve categories proposed for the Prince Edward Islands Marine Protected Area (see Fig. 7).

Reserve category	Area (km²)	% EEZ	Sum area (km²)	% EEZ
IUCN Category Ia - Ridge	17 926	3		
IUCN Category Ia - Islands	17 903	3		
IUCN Category Ia - Africana II Rise	9 438	2		
IUCN Category Ia - Abyss	23 157	4	68 425	13
Conservation Zones (axes)	112 208	21	112 208	21
IUCN Category IV (remainder of EEZ)	347 386	66	347 386	66
Total	528 019	100	528 019	100

Fig. 8. The relationship between the proposed Category Ia reserves (dark grey) and the Conservation Zones (light grey), and the three biodiversity patterns (fish target areas, seamounts and benthic habitats) whose targets are not met within these reserves.

along three main axes (Fig. 6). The bird and seal axes are in similar positions, radiating out from the islands in a north-west direction across the plateau area to the Southwest Indian Ridge, and in a south-west direction, again towards the ridge. Birds also use a third axis from the islands to the Africana II Rise, which forms part of the larger Del Caño Rise, which leads to the Iles Crozet farther east (Fig. 2). Although we were aware of spatial data for bird species tracked from the Iles Crozets that forage within the South African EEZ, these data were not included in our analyses but are mentioned later in the discussion.

Average positions of the fronts, as calculated by our study, are shown in Fig. 6d. The three foraging axes take birds and seals across these fronts, and therefore across their zones of variability (Lutjeharms & Valentine 1984). Although not shown in the figure, the APF regularly moves into the southern sector of the EEZ (Lutjeharms 1985).

Systematic conservation planning

The four Category Ia reserves defined in Step 1 are illustrated in Fig. 7 and described fully in Table IV. Their combined areas constitute 13% of the EEZ (Table V), and they meet all broad habitat and major water mass targets, as well as all fixed process targets. They also contribute substantially to all other targets (Table VI). No extractive activities may occur within IUCN Category Ia reserves, but although the northern three proposed Category Ia reserves do fall on fishing grounds specifically targeted during 1996–2005, most of the more recent fishing activity (2002–2005) is dispersed across the plateau region, and is
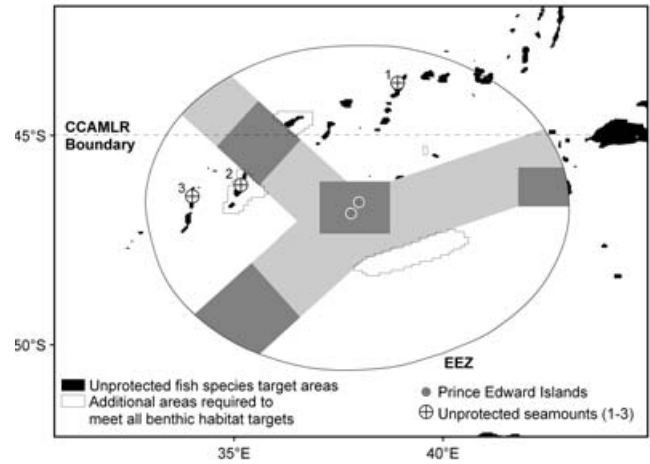
not concentrated in the proposed Category Ia reserves. The proposed Category Ia reserve in the south (Abyss) was not fished. Total fishing effort and catch data per planning unit are described in detail in Lombard (2006).

The three axes defined in Step 2 to meet flexible process targets constitute an additional 21% of the EEZ (Table V), and we have defined them provisionally as Conservation Zones, owing to the fishing grounds and shallower habitats present within them that require management and possible protection. These Conservation Zones also contribute substantially to outstanding targets (Table VI). Design rules were not compromised in Steps 1 and 2, and unmet targets at this point included 30% of the species rich fish areas, five benthic habitats, and three seamounts (Table VI).

To meet all benthic habitat targets, we used the C-Plan software in Step 3 to identify the smallest number of planning units, that were spatially clustered around the Category Ia reserves and Conservation Zones, that would meet outstanding benthic habitat targets, while simultaneously attempting to meet fish and seamount targets. Figure 8 shows that four additional areas are required: one small area of three planning units in the north east (for Upper slope–Thin sediment habitats); two other

Table VI. Summary of the conservation planning steps and targets met by each step (data in each row include data of previous row).

				Targets met			
Step	Description	No. of PUs[1] required	Fish	Benthic habitats (n = 21)	Seamounts (n = 11)	Fixed processes	Flexible process
1	Four Category Ia reserves	1135	46%[2]	6[3]	5[4]	All	Partially
2	Conservation Zones	3077	70%	16	8	All	All
3	Additional areas for benthic habitat targets	3508	77%	All	9	All	All

[1] Planning units, total number completely within EEZ = 9401
[2] 46% of 2-minute grid cells with ≥ four species
[3] Six of the 21 benthic habitats
[4] Five of the 11 seamounts

areas on the Southwest Indian Ridge (for Upper slope–Very thin sediment, and Lower slope–Very thin sediment habitats); and a larger area in the south-east to meet outstanding targets for Abyss–Medium sediments. However, these additional areas violate two of the design rules (they incorporate more recent fishing grounds and are not bordered by straight lines), while not substantially contributing to outstanding fish and seamount targets (Table VI). In order to meet all targets fully, the MPA would require all four areas of Step 3, as well as another axis running along most of the ridge and plateau within the EEZ (Fig. 8).

We thus recommend that the results of Steps 1 and 2 (Fig. 7) are used as provisional MPA boundaries, and that the remaining areas within the EEZ are classified as IUCN Category IV reserves (Habitat/Species Management Areas) in accordance with the CCAMLR proposal that the whole CCAMLR area be so classified (76% of the Prince Edward Islands' EEZ falls within the CCAMLR area). Biodiversity patterns with targets not met by the Category Ia reserves and Conservation Zones will therefore be able to benefit from a management strategy within these Category IV areas. The coordinates that define the reserve boundaries are provided in Lombard *et al.* (2005).

Discussion

Marine protected area design has received much attention in recent times, primarily because of the collapse of many fisheries globally (Pauly *et al*. 2002), and the negative ecosystem effects of fishing activities (Worm *et al*. 2005). Globally, we are now at the end of a 50-year period of intense fishing, and there is a transition between target stock management, to ecosystem management (Gell & Roberts 2003). The roles of MPAs as reference points, stock replenishment zones, management tools, scientific reserves, for the protection of threatened species and habitats, and as representative areas of marine habitats, are receiving increased attention and support (e.g. Kelleher 1999, Russ 2002, Gjerde & Breide 2003, Blundell 2004). Although the management of Southern Ocean resources is relatively well developed within CCAMLR, the protection of representative and threatened habitats, and habitats reserved for scientific study because of their pristine nature, is still in its infancy. We hope that this study will provide a starting point for further systematic studies in the region.

We stress that the fisheries benefits of MPAs are separate from the role of MPAs in biodiversity protection. Although we have addressed mainly the biodiversity benefits in this study, we emphasize that the MPA will be necessary for the recovery of depleted stocks of exploited Patagonian toothfish and will increase the yield of this collapsed fishery. The MPA is thus beneficial for biodiversity, as well as current fishery stakeholders.

Although the provisional MPA boundaries in Fig. 7 meet most of the targets defined for the study, the design rules force us to accept a compromise. This compromise means that the following targets fall outside of the Category Ia reserves and the Conservation Zones: 23% of the areas potentially rich in fish; remaining targets for five of the 21 benthic habitats; and three of the 11 seamounts. Meeting these targets will require the expansion of the Category Ia reserves and the Conservation Zones to include almost the entire northern half of the EEZ.

In this study, we have tackled the unknown effects of climate change by developing spatial surrogates for ecosystem processes, and by placing reserve boundaries to capture these processes. The boundaries also traverse latitudinal and longitudinal gradients, thereby maximizing the chances of incorporating the shifting position of the oceanic fronts. These fronts are critical to the offshore component of the Prince Edward Islands' life-support system, and operate over very broad scales. There is evidence that the average position of the SAF is shifting farther south, and that this movement is favouring the flow-through system that supports the offshore foragers, over the retention system that supports the inshore foragers (Pakhomov & Chown 2003). Ongoing monitoring of the bird and seal populations on the islands and their movement patterns, as well as of the positions of oceanic fronts, is required if we wish to modify the MPA boundaries in the future to cater for climate change.

We have suggested that the MPA boundaries proposed here may need to be changed in the future to accommodate shifting processes, and these changes may also be driven by new data becoming available. There are some obvious gaps in the data upon which this preliminary planning was based. For example, no data exist on the exact foraging grounds of fur seals, king penguins, and other bird species breeding on the Prince Edward Islands. However, foraging areas of seabirds tracked from the nearby Crozet Islands (sooty *Phoebetria fusca* Hilsenberg and wandering albatrosses and white-chinned petrels *Procellaria aequinoctialis* L., BirdLife International 2004), overlap largely with those from the Prince Edward Islands. Of note is the importance of the axis between the two islands, along the Del Caño Rise (Fig. 2). Many birds use this movement axis, and this emphasizes the importance of co-management of Southern Ocean resources by neighbouring countries, and the areas of the High Seas in between their EEZs.

Benthic habitat data are another obvious gap, and we attempted to overcome this problem by using bathymetry and sediment thickness data as habitat surrogates. Only quantitative surveys in the EEZ will enable us to test these surrogates, but at least our stratification of the EEZ can serve as a starting point for planning future surveys.

It is important to note that although a systematically planned MPA within the Prince Edward Islands will greatly enhance the conservation and management of this area, this measure should not operate in isolation. To be effective, the

MPA needs to be nested within an effective broader (and non-spatial) management framework for the Islands EEZ and the broader region. Marine ecosystems of the Prince Edward Islands are partially reliant on ecosystem processes that occur outside the EEZ, either within the Crozet Islands EEZ or on the High Seas (but within the CCAMLR area of jurisdiction). The foraging axis on the Del Caño Rise has already been mentioned. There is also a fracture zone in the Southwest Indian Ridge, to the South West of the islands and adjacent to the EEZ. This zone is an area of reliably high productivity, as a result of meso-scale eddies that are generated as the ACC crosses the ridge. These eddies are targeted by top predators breeding on the islands (Hofmeyr & Bester 1997, Klages & Bester 1998, Pistorius *et al.* 1999, Nel *et al.* 2001). It is therefore important that the South African MPA system around the Prince Edward Islands is nested within a regional spatial conservation plan for the CCAMLR region. It is comforting to know that moves are already afoot to develop just such a plan (CCAMLR 2005b). It is intended that the Prince Edward Islands MPA will be zoned for management purposes. The exact nature and regulatory regime of each zone remain under discussion, but recommendations for the three categories of reserves proposed in this study are provided in Lombard *et al.* (2005).

Recommendations

We conclude by summarizing our recommendations for the Prince Edward Islands MPA. Management and policy recommendations are provided in Lombard *et al*. (2005), and the spatial overlap of the proposed MPA with the legal fishery is presented in Lombard (2006). We recommend that:

1. The establishment of four IUCN Category Ia reserves (Fig. 7) to meet biodiversity targets, and for the recovery of the Patagonian toothfish fishery.

2. These four Category Ia reserves be connected via the Conservation Zones indicated in Fig. 7, in order to meet process targets (foraging grounds of top predators and oceanic frontal zones), and the long-term recovery of the toothfish fishery.

3. The rest of the EEZ be managed as an IUCN Category IV reserve, in accordance with CCAMLR proposals.

4. In order to detect climate changes that may impact the boundaries of the proposed MPA, sea surface temperatures and shifts in the position of the major frontal systems to the north and south of the islands be monitored.

5. In order to detect biotic responses to climate change, pelagic phyto- and zooplankton, and fish communities, and foraging patterns of birds and seals be monitored.

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