Mapping and Assessing Ecosystem Services provided by the Weddell Sea Area

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Declaration of originality

Hereby, I declare that this master thesis was written by me and that I did not use any other sources and means than specified. This master thesis was not submitted at any other university for acquiring an academic degree.

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ABSTRACT

The purpose of ecosystem services (ES) research is to integrate conservation and natural resource management into resource and land-use decision making. Investments in conservation should be recognized as profitable decisions both in regard to the economy and human well-being. However, for this to happen, and for policy and finance mechanisms to be established, a scientific basis is needed (Daily *et al*., 2009). For this reason, the main objective of this master thesis was to quantitatively assess and map three main ES provided by the Weddell Sea region: genetic resources, carbon sequestration and tourism. Additionally, synergies and trade-offs between the ES were explored. Another target pursued was to examine the influence of sea ice cover on the service delivery. This is the first time the Weddell Sea is subject to a detailed regional ES assessment. The present study should contribute to the proposal for a Weddell Sea marine protected area (MPA) expected for consideration in October 2015 at the earliest. The analyses conducted during this study covered both spatial and temporal correlations between pairs of ES, and between individual ES and sea ice coverage. The outcome shows that there are indeed areas where multiple benefits are provided simultaneously ("super hotspots"). In general, though, service delivery in the studied seacape is distinctively heterogeneous. This result calls for cautiousness in relation to expectations that small-scaled conservation efforts achieve their intended goals. The results also show that particularly tourism is closely connected to sea ice cover, which is the reason why this sector could experience strong growth in view of global warming.

Key words:

Ecosystem services, Weddell Sea, trade-offs, synergies, sea ice, Geographic information system

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Abbreviations

AMSR-EOS	Advanced Microwave Scanning Radiometer - Earth Observing System
AOA	Antarctic Ocean Alliance
ArcGIS	A proprietary geographic information system (GIS) software platform from ESRI
ASI	ARTIST Sea Ice
ATS	Antarctic Treaty System
AWI	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), Bremerhaven, Germany
BMEL	Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of food and Agriculture, Germany)
CBD	Convention on Biological Diversity
CCAMLR	Commission on the Conservation of Antarctic Marine Living Resources
chl *a*	Chlorophyll *a*
CO_2	Carbon dioxide (chemical formula CO_2)
CS	Coldspot(s)
CV	Spatial covariance of the dataset
Dec	December
E	East
ES	Ecosystem Service(s)
ESRI	Environmental Systems Resource Institute
Feb	February
GIS	Geographic information system
HS	Hotspot(s)
IAATO	International Association of Antarctica Tour Operators
IDW	Inverse Distance Weighted Interpolation
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs tool
IPCC	Intergovernmental Panel on Climate Change
IUU	Illegal, unreported and unregulated (IUU) activities e.g. fishing
Jan	January
km	Kilometer
km^2	Square kilometer
m	Meter
m^2	Square meter
m^3	Cubic meter
MAPS	Marine Mammal Perimeter Surveillance
Mar	March

Max	Maximum value
MEA	Millennium Ecosystem Assessment
Mg	Milligram
Min	Minimum value
MPA	Marine Protected Area
N	The amount of samples/values
NA	Not available = missing value
NASA	National Aeronautics and Space Administration
Nov	November
Oct	October
QGIS	Quantum GIS, an open-source desktop geographic information system (GIS) application
RV	Research vessel
S	South
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
StdDev	Standard deviation
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations
UNEP	United Nations Environment Programme
W	West
WAP	Western Antarctic Peninsula

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1. INTRODUCTION

Burkhard *et al*. (2012) perceive the quantification of ecosystem goods and services as one of the biggest challenges of current ecosystem science. Not only due to a lack of appropriate methods, but also as a consequence of the spatial and temporal peculiarity. This is especially true for the marine domain where the assessment of the provision of ecosystem services (ES) is hindered by a lack of appropriate data and methods (Barbier, 2012; Costanza, 1999; Markandya *et al*., 2008; UNEP, 2012a; UNEP, 2012b). Furthermore, the complexity of the topic lies in the fact that ES produced by the (open) oceans seldom have on-site beneficiaries (Grant *et al*., 2013). Instead, they may support consumption in the most diverse places in the world (Catarci, 2004; Grant *et al*., 2013; Nicol *et al*., 2012). The same applies to regulating and supporting services such as climate regulation, ocean circulation and nutrient cycling which are beneficial on a global scale (Costanza, 2008; Grant *et al*., 2013). One example are marine genetic resources ("blue gold") which enhance scientific understanding, and are valuable for (potential) use and application in medicine and agriculture all over the world (Oldham *et al*., 2014; UN, 2010).

The negative side-effect of the branched and long-chained linkages from ES to their beneficiaries is that the connections between the health of marine ecosystems and economic decisions and human well-being elsewhere are blurred. Many parties are not fully aware of their dependence and impact on these far off ecosystems (CBD, 2015). In addition, there is, literally, much room for the diffusion of responsibility. This is particularly true when it comes to the conservation of these ecosystems. A paradigm shift linking beneficiaries to ecosystem functions is of particular importance considering that the increasing (anthropogenic) pressures on natural resources alter environmental processes irreversibly (MEA, 2005a). There is an urgent need for increased credibility and transparency in ecosystem management (Daily *et al*., 2011; Jopke *et al*., 2014; Koellner, 2011). An important step in this direction is the assessment and mapping of ES, and the assessment of the way multiple ES are coupled in bundles (TEEB, 2010a). This represents a major gap in previous research (Carpenter *et al*. 2009). The situation is aggravated by the fact the Weddell Sea region is under-represented in global ecosystem assessments (e.g. UN, 2005; UNEP, 2010, 2012) and not yet the subject of any detailed regional ES assessment (Grant *et al*., 2013). This is probably because the importance of Southern Ocean ecosystems is still not fully perceived which is reflected in the low number of studies in this region, e.g. compared to the North Sea.

This study should contribute to the proposal for a Weddell Sea MPA expected for consideration by the Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR) in October 2015 at the earliest. In this context, the objectives of this research are: (i) the quantitative mapping and assessing of the ES provided by the region; (ii) to identify synergies and trade-offs between ES; and (iii) to determine if ES are related to the sea ice cover of the region. It is important to include sea ice cover in the analyses because of its influence on life cycles and productions of flora and fauna in the study area (Flores, 2009).

Furthermore, this master thesis is the implementation of the United Nation's clarion call for increased and concerted research on measuring and mapping ES (Carpenter *et al*., 2006a; Fisher *et al*., 2009; Sachs and Reid, 2006; UN, 2005). This extends previous knowledge, particularly because most studies so far have focused on single services only, mostly provisioning services (Tallis and Polasky, 2009; UNEP, 2011).

The Ecosystem Service Framework

In recent years, considerable attention has been drawn to the ES framework (Fisher *et al*., 2009; Gómez-Baggethun *et al*., 2009). Daily and Matson (2008) compare this development to a "growing feeling of Renaissance in the conservation community", aligning economy with nature conservation and thereby addressing more diverse and powerful leaders and a new and larger source of conservation funding than past approaches (Daily and Matson, 2008; Simpson, 2011; Tallis and Kareiva, 2005). Interest in the benefits people obtain from ecosystems (Daily *et al*., 2009; MEA, 2005b; TEEB, 2010a) was aroused in the light of increasing pressure and stress on ecosystems (Jopke *et al*., 2014). In the case of this research area, these threats are mainly represented by climate change (e.g. AOA, 2013; Boyd *et al*., 2012; Teschke *et al*., 2015a; IPCC, 2014; Massom and Stammerjohn, 2010; Monien *et al*., 2011; Murphy *et al*., 2012; Peck and Conway, 2000; Wittmann and Pörtner, 2013) and the fishing industry's increasing ambition for toothfish and krill (AOA, 2013; Brey, 2014; MEA, 2005a). Tourism might also become a determining factor in the future, if the sector increases significantly (Teschke *et al*., 2015a).

Initiated by the Millennium Ecosystem Assessment (MEA), four different types of ES are usually recognized: (i) provisioning services (e.g. food, water, and timber); (ii) regulating services with effects on climate, floods, disease, waste, and water quality; (iii) cultural services with recreational, aesthetic, and spiritual benefits; and (iv) supporting services (e.g. soil formation, photosynthesis, nutrient cycling) (MEA, 2005b). Even if this classification is not without criticism (see Boyd, 2007; Boyd and Banzhaf, 2007; Costanza, 2008; Fisher and Turner, 2008; Hattam *et al*., 2015; Koellner, 2009; Wallace, 2007; Wallace, 2008), one of the major unchallenged findings was that ecosystems have declined more rapidly and extensively over the past 50 years than during any other comparable time period in human history (MEA, 2005b). Marine ecosystems are amongst the ecosystems most significantly altered globally by human activity (MEA, 2005b). The MEA states fishing activities as driver with the greatest impact on living marine resources and their associated ecosystems over the last 50 years (MEA, 2005a).

Antarctica and ES

The ES approach is not only endorsed by the MEA but also by the Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR). The premise is that conservation and sustainable use are promoted in an equitable way in waters surrounding Antarctica (Beaumont *et al*., 2007; CBD, 2000). A holistic view is taken on the essential structures, processes, functions and interactions among organisms (e.g. predator-prey interactions) and between organisms and their environment (CBD, 2000). Humans are considered an integral component of the system (CBD, 2000; McLeod and Leslie, 2009; Rosenberg and McLeod, 2005; UNEP, 2005). In addition, cumulative impacts are given explicit attention (ATCPs, 1991). Article II of the CCAMLR Convention is based on three principles: the first aim is the prevention of population decline to levels threatening stable recruitment of harvested species. Secondly, harvesting activities should not be conducted at the expense of ecological relationships between the harvested, dependent and related species. Finally, ecosystem changes that are not potentially reversible within 20 to 30 years are to be minimized (CCAMLR, 2013). Yet, progress in the practical integration of a precautionary ecosystem approach in land-use planning, management and conservation programs is still lagging behind the necessity (e.g. Daily *et al*., 2009; Naidoo *et al*., 2008). In most cases, and for most services, there is little incentive for decision makers to account for the continued provision of ES (Tallis and Polasky, 2009). One example is the illegal, unreported and unregulated (IUU) fishing of the Patagonian toothfish (*Dissostichus eleginoides*) and the Antarctic toothfish (*Dissostichus mawsoni*) (Agnew, 2000; MEA, 2005a). Selling price for toothfish, also referred to as “white gold” (CCAMLR, 2014), has reached record highs (CCAMLR, 2012a). Comparable to the illegal clearing of mangroves described by Tallis and Polasky (2009), those conducting IUU activities receive high market prices, but they do not bear the full cost associated with the loss of the fish species as part of an integrated and interrelated ecosystem (CCAMLR, 2014). The problem of IUU may become more compounded in the Weddell Sea area if access to the area becomes less restricted by sea ice (Teschke *et al*., 2015a; MEA, 2005a).

2. RESEARCH OBJECTIVE AND HYPOTHESES

Until now the ES framework has not been applied to the Weddell Sea area as mentioned above. This master thesis aimed to identify, quantify and map genetic resources, carbon sequestration and tourism in the study area, and to assess trade-offs and synergies between them. It is important to note that the seasonal cycle of sea ice cover plays a critical role in the Southern Ocean not only due to its contribution to the global thermohaline circulation through deep and bottom water formation (Flores, 2009; Haid and Timmermann, 2013), but also with regard to both productivity and accessibility (ACE, 2015; Flores, 2009; Moore and Abbott, 2000; Murphy *et al*., 2012). For instance, Moore and Abbott (2000) identified a significant relationship between sea ice and chlorophyll *a* (chl *a*) distribution.
Furthermore, phytoplankton holds a key position in the Weddell Sea system. Studies show a positive relationship between chl *a* concentration and the occurrence of zooplankton species (Teschke *et al*., 2015c). This is, for example, illustrated by Atkinson et al. (2004) who reveal a positive correlation between chl *a* concentrations and mean krill density. Moreover, even mammal occurrences like humpback whales are associated with areas of high chl *a* density (e g ir ovi and ildebrand, 2011; Thiele *et al*., 2000). These species belong to the target species of tourists in the region. Summarizing, it can therefore be said, that there is a clear trajectory of ecosystem components from sea ice cover, over phytoplankton, zooplankton, and nekton to top predators like birds, seals and whales (Flores, 2009). Hence, the following hypotheses will be tested:

Hypothesis 1: Ultimately, the provision of all ES in the study area boils down to chl *a* concentrations.

Hypothesis 2: Sea ice cover is a major limiting factor for the provisioning of ES in the Weddell Sea study area.

3. MATERIALS AND METHODS

Study Area

Boundaries and ecosystems

For the purpose of this investigation, the Weddell Sea area was selected. To avoid that important tourism areas were excluded from the analyses, the research frame was extended beyond the boundaries of the MPA planning area (see Teschke *et al.*, 2015a) in the East (20”E) and beyond the Western Antarctic Peninsula (WAP) in the West (Fig.1). With that, the study area covers also areas in the Bellingshausen Sea along the west side of the Antarctic Peninsula and in the Lazarev Sea. The study area covers approximately 7.7 million km², with an extension from 60°S in the north to the continental and shelf ice margin in the south (about 75°S) and an East-West extension from about 75°W to 25°E.

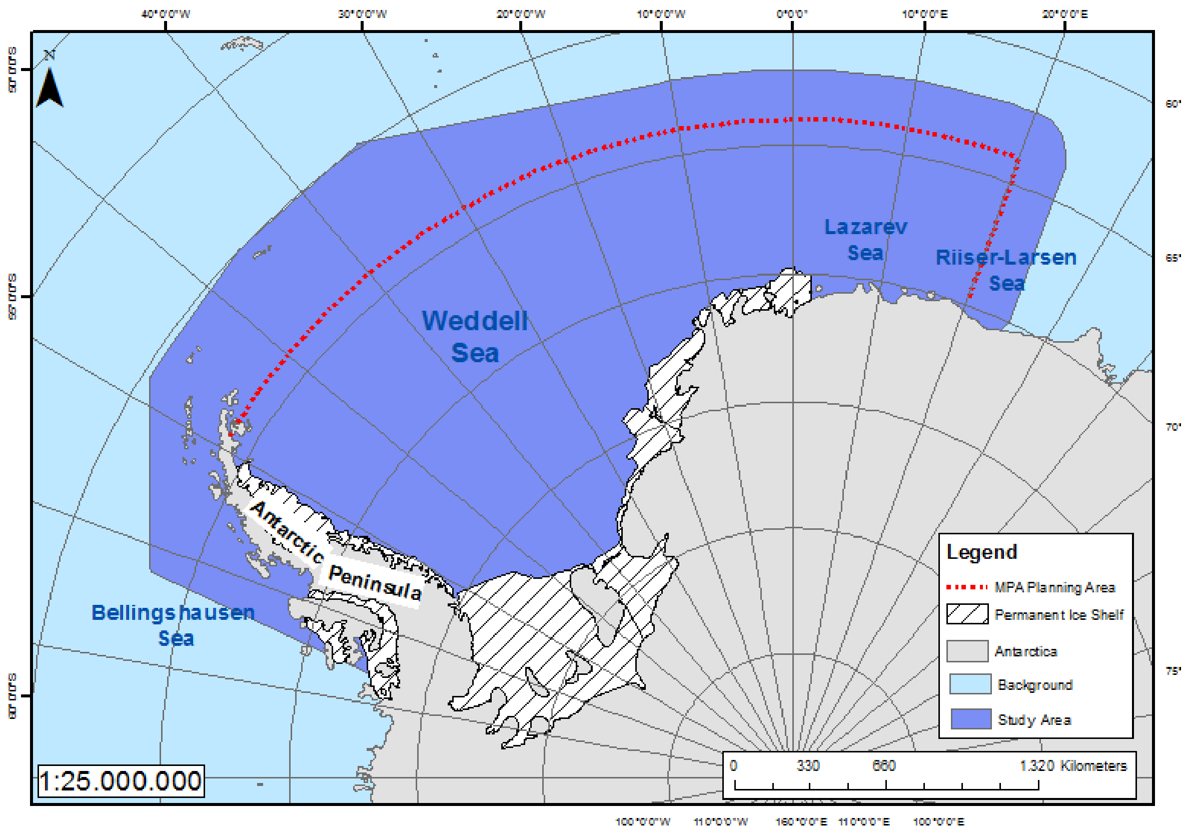


Figure 1 Map showing the study area.

Much of the study area is permanently covered with ice, for instance the Filchner-Ronne Ice Shelf. However, the research site encompasses diverse ecological values. It comprises almost the full spectrum of geomorphic features of the Southern Ocean seafloor, ranging from about 100 m at the edge of the ice shelf and 5000 m in the Weddell Sea abyssal plain (AOA, 2013; Teschke *et al*., 2015a). Furthermore, a number of important features are known to commonly support vulnerable marine ecosystems (e.g. Filchner Trough, shelf-commencing canyons, banks, seamounts, shelf deeps, ice shelf cavities and cross-shelf valleys) (AOA, 2013; Teschke *et al*., 2015a). The unique and mostly untouched communities and ecosystems have adapted to the harsh and isolated Antarctic living conditions over millions of years, resulting in a high number of endemic species (AOA, 2013; Clarke and Johnston, 2003; Flores, 2009). This endemism demonstrates the unsurpassed importance of the Weddell Sea's genetic resources. The region holds a key position with regard to its uniqueness, naturalness, diversity, in combination with the important role in the near future in providing a place of refuge for ice dependent, pelagic key ecosystem components (e.g. Antarctic krill, *Euphausia superba;* ice krill, *Euphausia crystallorophias;* Antarctic silverfish, *Pleuragramma antarcticum;* sea birds; marine mammals) (Teschke *et al*., 2015a). This would characterize the research area as an underestimated ecologically and biologically significant marine area (CBD, 2012). These characteristics satisfy the CBD (2012) criteria for areas in need of protection on the way to a representative network of marine protected areas (Gjerde *et al*., 2013).

As one of the most intact ecosystems left on earth, the region is also an important reference area for fundamental scientific research primarily influenced by natural ecological processes (AOA, 2013; BMEL, 2014).

Governance

The governance system of Antarctica is established by a set of international agreements also known as the Antarctic Treaty System (ATS) (Grant *et al*., 2013). These treaties emphasize that with every management activity impacting ecosystems particular attention is to be paid to trade-offs (ATS, 2011; Grant *et al*., 2013). CCAMLR entered into force in 1982 and underpins the management of (fishing) activities in the Southern Ocean. It applies to all marine living resources within the area south of the Antarctic Convergence (CCAMLR, 2012b). The primary objective of this convention is the conservation of Antarctic marine flora and fauna, where conservation includes "rational use" (Grant *et al*., 2006, 2013). Therefore, CCAMLR's main responsibility is the regulation of fishing activities, especially for toothfish, crab and krill – key organisms of the Antarctic food web.

ES Assessment

ES assessments usually involve the following dimensions: First, there is a biophysical assessment of the structure and the functions of a site. Subsequently, an assessment of the value per unit of services is conducted followed by the mapping of services provided (Galparsoro *et al*., 2014; Schägner *et al*., 2013). In addition, trade-offs and synergies between ES are identified to evaluate the spatial correspondence of different benefits (de Groot *et al*., 2010; Schägner *et al*., 2013). Finally, the economic value of ES would be estimated. However, the latter was excluded from this investigation. The reason for this is that in order to conduct an economic valuation, there needs to be comprehensive knowledge and data of the ES of a region (Galparsoro *et al*., 2014), which is an outcome of this study.

Selecting an ES classification

There is a great number of approved ES classifications already in use (Fisher *et al*., 2009; Hattam, 2015). One of them is a classification by Grant *et al*. (2013). This classification scheme was inspired by the MEA classification and carefully modified and adapted to suit the services in the seascape of the Southern Ocean. This spatial correspondence made the classification particularly suitable for the current study, which is why it was selected. Three ES that included provisioning, regulating and cultural services were quantified and mapped at 1000-m spatial resolution for the Weddell Sea region. These services were selected based on the availability of data and the fact that they had to be characteristic for the study area with global significance. Applying the above criteria, the following ES were selected:

a) genetic resources (provisioning ES)
b) carbon sequestration (regulating ES)
c) tourism (cultural ES)

The analysis excluded supporting services as they provide the basis for other types of services. Thus, it was assumed that their contribution would be captured by the assessment of other ES (Queiroz *et al*., 2015). Another reason for the exclusion of supporting services is their controversial classification. Some would rather classify them as “ecosystem functions” underlying the production of provisioning, regulating, and cultural services (Queiroz *et al*., 2015; TEEB, 2010b).

Instead of using absolute metrics to classify service provisioning, the assessment was based on the following guideline: if a service was provided by an area but to a substantially lower magnitude than by other areas, a “Low” value was assigned If the services was provided to greater extent by one region than by another a ” igh” value was assigned (Galparsoro *et al*, 2014). A similar classification and score was successfully used in other studies (see Galparsoro *et al*, 2014; Potts *et al*., 2014).

ES proxies

Because many services cannot be measured directly, biophysical and ecological proxies were used. As already applied by Hattam *et al*. (2015) and Burkhard *et al*. (2012), proxy usability was tested against criteria defined by Link *et al*. (2009), Dale and Beyeler (2001) and van Oudenhoven *et al*. (2012). These criteria applied to the current study imply that proxies need to be measurable and sensitive to changes in marine habitats and ocean uses. A two stage process, similarly applied by Hattam *et al*. (2015), was used for the selection of proxies: The first step was the identification of proxies for the respective marine ES during interdisciplinary expert discussions. These discussions were particularly important to gain an overview over the state of the art. Secondly, the proxies which had been agreed upon were adapted to fit the Weddell Sea case study (Table 1).
Furthermore, the selection of proxies was supported by previous studies. These, for instance, reinforce the assumption that chl *a* concentration is a suitable proxy for phytoplankton biomass, which means that it is suitable for exploring spatial heterogeneity in primary production on a large scale (e.g. Moore and Abbott, 2000; Grant *et al*., 2006). This is true even if the proxy of choice may not mirror primary production absolutely (Grant *et al*., 2006).

Table 1 Types and proxies of ES assessed in the study area.

Type	ES	Proxy	Unit
Provisioning services	Genetic resources	Higher benthic taxa	N/m^2
Regulating services	Carbon sequestration	Chl *a* concentration	mg/m^3
Cultural services	Tourism	Tourism visitation	Number of tourist per site
		Touristic ship traffic	Number of times that a location was traversed by a ship

Mapping ES

Maps are an effective means to characterize current benefits society derives from ecosystems. In addition, they support the adoption of sustainable management measures thereby contributing to human welfare and well-being (Egoh *et al*., 2012; Galparsoro *et al*., 2014). In fact, they ensure transparency of trade-offs and synergies associated with decisions concerning ecosystems (Grant *et al*., 2013). These trade-offs are inherent in most decisions about ES (Rodriguez *et al*., 2006), not only between different services, but also between the current and potential future supply of a service (Carpenter *et al*., 2006b). This makes the visualization of ES a powerful tool for decision makers (Burkhard *et al*., 2012; Swetnam *et al*., 2010). Yet, marine ES mapping represents a particular challenge compared to terrestrial assessments. There are two main reasons for this: one problem is the low resolution or even absence of spatially explicit information, and the second problem is the challenges that a highly dynamic 3D environment presents (Galparsoro *et al*., 2014; Liquete *et al*., 2013; Maes *et al*., 2012; Somerfield *et al*., 2008). At this stage, explicit trade-off analysis in the marine realm is rather exception than rule (IPBES, 2012; UNEP, 2012b). Consequently, this thesis aims to close an important research gap in the field of the ES framework.

Preliminary Data Retrieval

To collate information on the status and distribution of genetic resources, carbon sequestration and tourism in the study area, different environmental and ecological data sets were analyzed. The primary datasets used in this analysis were data on macrozoobenthic taxonomic richness, mean chl *a* concentration values and ship-born tourism concentration. The secondary datasets represent features particularly important to the provisioning of ES, including sea ice cover, as well as data on flagship species (Zacharias and Roff, 2001) such as penguin abundance and whale sightings (Grant *et al*., 2013). The latter was used as an indicator for potential touristic activities in the future. During the last 30 years, national and international research activities have yielded a tremendous amount of such data. Since the icebreaking research vessel (RV) *Polarstern* concentrated on shelf areas of the southern and eastern Weddell Sea, ecological studies also tend to focus on these areas (Teschke *et al*., 2013).

Primary data sets

Higher benthic taxa

Macrozoobenthic taxonomic richness at the level of higher taxonomic groups (class or phylum) was calculated from a data set held by D. Gerdes (AWI) and U. Mühlenhardt-Siegel (German Center for Marine Biodiversity Research, DZMB). The data was sampled at specific sites within the study area based on expert knowledge. Some of the most remote samples (Fig. 2, pink dots) were excluded from the analysis because they would have led to extreme spatial mismatch between this data and other data sets used.

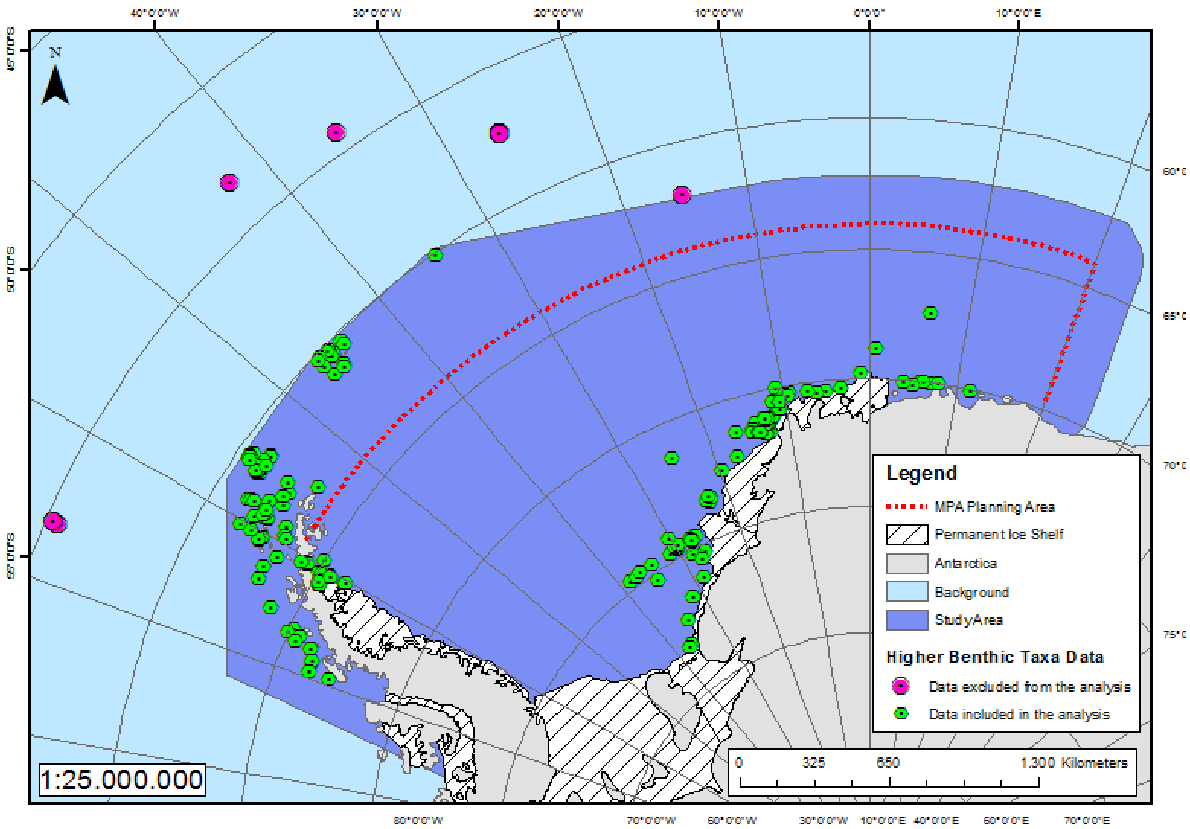


Figure 2 Data on higher benthic taxa that was included and excluded from the analyses. Exclusion was undertaken as a result of extreme spatial remoteness compared to the spatial extent of other proxies used.

Chl a concentration

Chl *a* concentrations within the study area derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) measurements for the period 1997 through 2010. The data was downloaded via the NASA's OceanColor website (http://oceancolor gsfc nasa gov/) as monthly level 3 standard mapped images with a spatial resolution of 9 km x 9 km. Data gaps were caused by clouds, ice and low incident light. Only austral summer (Nov-Mar) chl *a* data were considered as a consequence of short day length, the inability of SeaWiFS to produce accurate chl *a* estimates at very high solar angles and high sea ice concentration in most parts of the study area during austral winter (Moore and Abbott, 2000).

Tourism sites and touristic ship traffic

Data on tourism visitation (excluding recreational visits by research station personnel) was provided by the International Association of Antarctica Tour Operators (IAATO). The data used reflects approximately 95 % of all of the commercial cruise ships operating on the Antarctic Peninsula and approximately 90 % of all the known visitors to the area (Lynch *et al.*, 2009). The records of site-specific landings are available going back to the 2000-2001 season. However, only data reaching back to the 2003-2004 season was used. This is for reasons of comparability, because the pre-2003 data format differs from later data sets. Digital records include information on locations and time for passenger activities. Information on ship routing between stops is not included in the IAATO data. To reconstruct ship tracks from activity locations at the Antarctic Peninsula, Lynch *et al*. (2009) divided the Antarctic Peninsula waters into grids of squares with grid nodes spaced 6 km apart. Travel between nodes was permitted in the four cardinal directions. Ship track construction was conducted using the 'GraphPath' Function in Mathematica (Wolfram Research, 2007). These reconstructed ship routes disregard routing measures designed to avoid sea ice, high winds, or other itinerant conditions. Also neglected is scenic cruising not involving passenger disembarkment.

The analysis by Lynch *et al*. (2009) was verified by ground truthing based on the personal knowledge of ship officers experienced in Antarctic Peninsula cruises.

Secondary data sets

Sea ice concentration

The monthly mean sea ice concentration data used from 2002 to 2011 was derived from a former study by Teschke *et al*. (2015b) and cropped to the spatial extent of the study area (Fig. 3). Used were the total monthly average values for October to March, i.e. the time of austral summer.

The data set contains satellite observations of daily sea ice concentration derived from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-EOS) instrument on board the Aqua Satellite. Teschke *et al*. (2015b) downloaded high resolution AMSR-E 89 GHz circum-Antarctic sea ice concentration maps (Jun 2002 to Oct 2011) from the Institute of Environmental Physics, University of Bremen (http://www.iup.uni-bremen.de/). The ARTIST Sea Ice (ASI) concentration algorithm with a spatial resolution of 6.25 km x 6.25 km was applied (Kaleschke *et al*., 2001; Spreen *et al*., 2008).

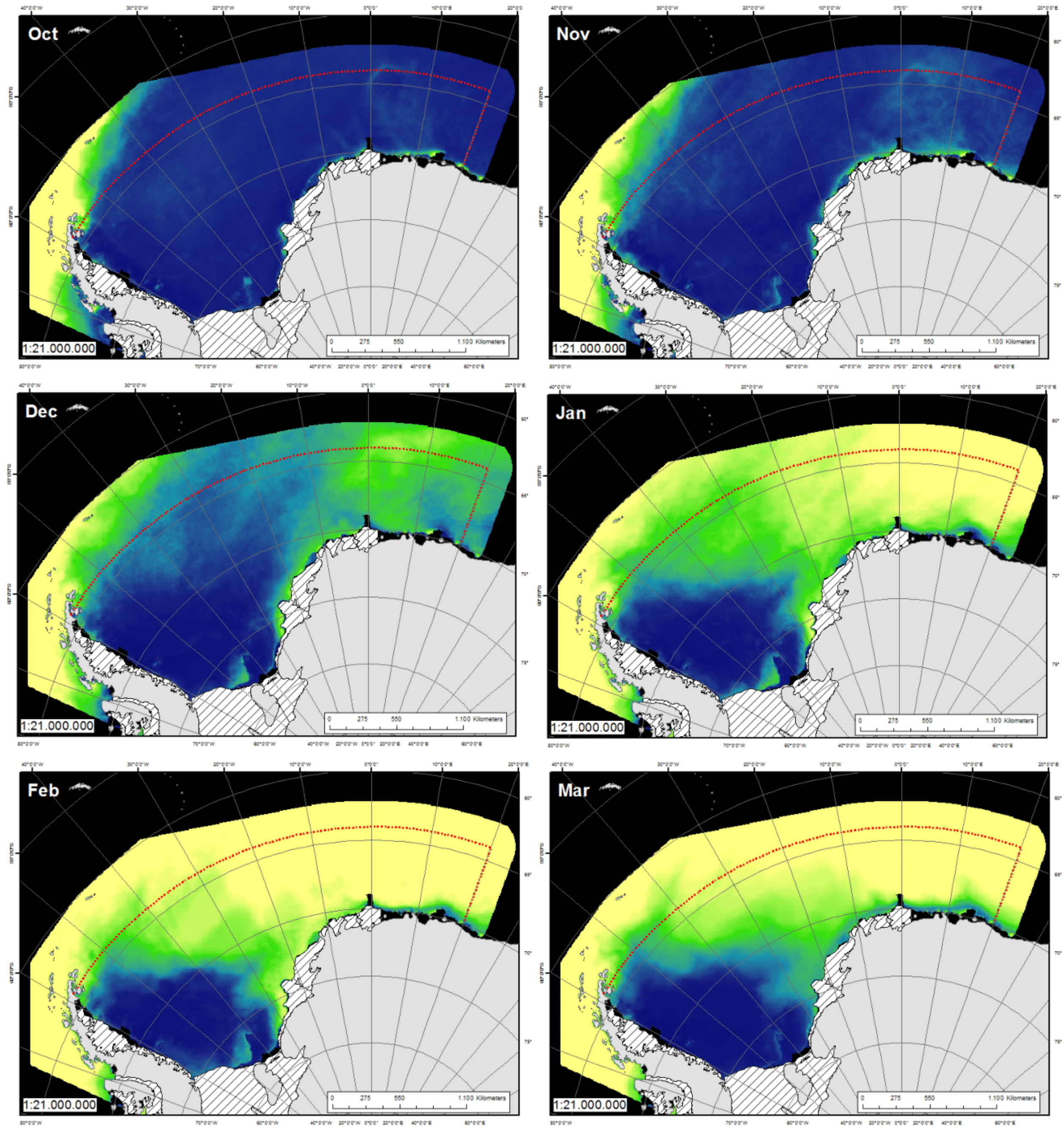
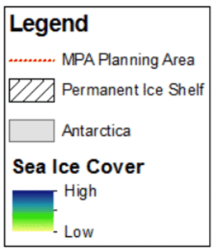


Figure 3 Monthly mean sea ice cover (Oct to Mar 2002-2011) in the study area based on AMSR-E 89 GHz sea ice concentration data (Spreen *et al.*, 2008). Black indicates areas beyond the spatial extent of the Weddell Sea study area.



Penguins

Data on emperor penguin (*Aptenodyptes forsterii*) population estimates were derived from Fretwell *et al*. (2012, 2014). This data set was complemented by unpublished data on Adélie penguin (*Pygoscelis adeliae*) colonies from Heather Lynch, Stony Brook University, USA.

Whales

Since 2005, the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), systematically and continuously logs all sightings of cetaceans, e.g. humpback whales (*Megaptera novaeangliae)* and Antarctic minke whales (*Balaenoptera bonaerensis)*, near RV *Polarstern* in the Southern Ocean (Marine Mammal Perimeter Surveillance, MAPS).

Table 2 List of parameters, data sets (incl. spatial and temporal resolution) and data sources.

Parameter			Sampling design and temporal resolution			Source (contact person, publication, web site)
			Sampling Design	Periode	Temporal Resolution	
Primary Data Sets	**Genetic Resources**	Higher benthic taxa	Various German Antarctic expeditions; almost 300 samples	1984-2011	Different time intervals	Data set held by D. Gerdes and U. Mühlenhardt-Siegel
	Carbon sequestration	Chl *a* concentration	0.83 km x 0.83 km	1997 - 2010	daily	National Aeronautics and Space Administration (NASA) Goddard Space Flight
	Tourism	Tourism visitation		2003-2014	annual	IAATO http://iaato.org/de/tourism-statistics
		Touristic ship traffic		2003-2008	annual	Lynch *et al*. 2009
Secondary Data Sets	**Sea ice cover**	Sea ice concentration	AMSR-EOS	2002-2011	monthly	Teschke *et al*. (2015b)
	Penguins	Adélie penguin breeding colonies	high resolution (0.6 m) satellite imagery with spectral analysis	2000s	Snapshot in time	H. Lynch, Stony Brook University, USA (unpublished data)
		Emperor penguin breeding colonies	High resolution satellite imagery	2009, 2012	Snapshot in time	Fretwell *et al*. (2012, 2014)
	Mammals	Whales	15 *Polarstern* cruises; Opportunistic cetacean sightings	2005 - ongoing	Snapshot in time	Burkhardt (2009 a-i, 2011, 2012 and unpublished data); Bombosch et al. (2014)

Analytical Methods

All data listed in Table 2 was imported into QGIS (version 2.8.1) – an open-source desktop geographic information system (GIS) application (QGIS Development Team, 2015) – for data representation and preparation. For all data layers WGS 84 / NSIDC Sea Ice Polar Stereographic South (EPSG-Code: 3967; http://nsidc.org/data/atlas/epsg_3976.html) was used.

Calculations and analyses were mainly done with R (version 3.1.3.). R is a programming language and software environment for statistical computing and graphics (R Core Team, 2015). Maps were designed using the GIS-software ArcGIS (version 10.2.2, ESRI, 2013). ArcGIS is a proprietary geographic information system (GIS) software platform by ESRI (Environmental Systems Resource Institute). The spatial distribution of the proxy values for each service was plotted on the basis of 1000-m grid cells. Extreme values were kept in the dataset for two reasons: Firstly, a purely statistical evaluation of data points as outliers does not meet the case. Secondly, the research area is quite data-poor, i.e. leaving out data points would render the analysis very difficult.

Data transformation

Many scientific publications on statistical methods in ecology suggest the use of data transformation (e.g. log-transformation) to normalize count data (e.g. Crawley, 2003; Cuesta *et al*., 2008; Magura *et al*., 2005; Maindonald and Braun, 2007) Nevertheless, O’ ara and Kotze (2010) revealed that count data is not suitable for transformation. This is due to the fact that count data often contains many ‘zero’ observations (see Sileshi *et al.,* 2009) and are unlikely to have a normally distributed error structure. Thus, transformations perform poorly, especially if dispersion is wide and the mean counts small. O’ ara and Kotze (2010) showed that count data should not be analyzed by log-transforming to avoid bias and misinterpretations. This view is also supported by Grant *et al*. (2006), who point to the danger that through transformations of data, properties of variables and their relationships to other variables could be altered. This is the reason why, in this study, the count data on tourism activity and benthic taxa were not log-transformed. Instead, their raw values were used for the analysis. Log-transformation was only used to explore chl *a* concentrations.

Inverse Distance Weighting (IDW)

Data on genetic resources and tourism (all point data) were used to create interpolated raster surfaces using the Inverse Distance Weighted (IDW) function in the Spatial Analyst toolbox of QGIS 2.8.1. For more details see Burrough and McDonnell (1988) and Lu and Wong (2008).

The range of higher benthic taxa often shows correlations with biological, ecological and physical attributes of the seafloor (Kostylev *et al*., 2001). Some of these attributes are used to divide the seafloor into different marine bioregions (Grant *et al*., 2006), and can be suitable to define benthic species distribution ranges. Here, the IDW was limited by a 30 km buffer corresponding to the minimum mean distance of the sampling stations to the border of the specific marine bioregion they are situated in. Furthermore, the 30 km-buffer has frequently been used in the analyses conducted for the Weddell Sea MPA project, which ensures comparability.

The assessment of the provisioning of tourism (tourism visitations and touristic ship traffic) is also based on IDWs as tour operators construed their itineraries in accordance with sea ice and weather conditions. The consequence is that ship routes are kept very flexible covering more than the theoretically planned area.

Hotspots and coldspots

Following Egoh *et al*. (2008), hotspots are considered as areas providing large proportions of a particular service, whereas coldspots refers to the opposite situation. In deviation from the original definition by Myers (1988), the notions do not imply levels of threat or endemism.

In the scientific literature, the threshold for defining service hotspots and coldspots is inconsistent. Here, the approach mentioned in Gimona and van der Horst (2007) and Locatelli *et al*. (2014) were followed, and thus the quartiles were chosen as cut-off points. Consequently, hotspots and coldspots of a given ES are areas with values in the highest and lowest 25 % range of all values, respectively (Locatelli *et al*., 2014). For tourist visitation and tourism-related ship traffic complete documentation of the tourism occurrence in the raw data was assumed, i.e. missing values (NAs) were considered as coldspots. Following Qiu and Turner (2013), hotspots and coldspots of more than one ES were identified by overlaying and summing raster maps of the upper and lowest 25th percentile of each service, respectively. Super hotspots and super coldspots were considered as areas with two or more services in the highest and lowest 25th percentile, respectively. Gimona and van der Horst (2007) call these areas "multifunctional hotspots", and Myers *et al*. (2000) speak of "the hottest hotspots".

Since both tourism visitation and touristic ship traffic together are used to map tourism provision, these indicators are considered as a whole at some points. Hotspots of both proxies were kept as hotspots, and areas were both data sets had hotspots were recorded once as hotspot. For coldspots, the rule was that only areas where both layers had extreme lows were considered as coldspots in the new tourism layer.

Trade-offs and synergies

Trade-offs and synergies were assessed to identify congruence or divergence between ES, and between individual ES and sea ice cover. A similar goal was pursued by Locatelli *et al*. (2014). To measure the strengths of trade-offs and synergies between pairs of ES and between individual ES and ice cover, Pearson's correlations were calculated using the R package ‚stats' (R Core Team, 2015)

4. RESULTS

In the following chapter, the results regarding (i) spatial distribution patterns of ES, (ii) ES hotspots and coldspots, and (iii) interactions between ES, and between ES and ice cover are presented.
The corresponding maps show the spatial distribution of the provisioning service genetic resources, the supporting service carbon sequestration, and the cultural service tourism.
The legends were classified on the basis of the data's overall standard deviation. The lower limit of the scale is the overall minimum value of the data, whereas the upper limit of the scale is the overall maximum value.

Production and Spatial Distribution of ES

Genetic resources

A maximum of 32 different taxa at the level of higher taxonomic groups (Table 3) occurred in the study area. No area showed less than three taxa with an average number of 16. However, standard deviation was quite high. Figure 4 shows the distribution of genetic resources in the study area. Higher taxa variety was not equally distributed. It becomes obvious that the ES provisioning was generally high offshore Queen Maud Land, beyond Fimbul Ice Shelf in the East, and extending over Ekstrøm to Jelbart and Brunt Ice Shelf in the South-East.

Table 3 Summary statistics of the higher benthic taxa (in individuals/m²).

Parameter	Value
Mean	15.52
Standard deviation (StdDev)	6.01
Sum	4144.0
Minimum value (Min)	3.0
Maximum value (Max)	32.0
The amount of samples/values (N)	267.0
Spatial covariance of the dataset (CV)	0.39
Range	29.0
Median	15.0

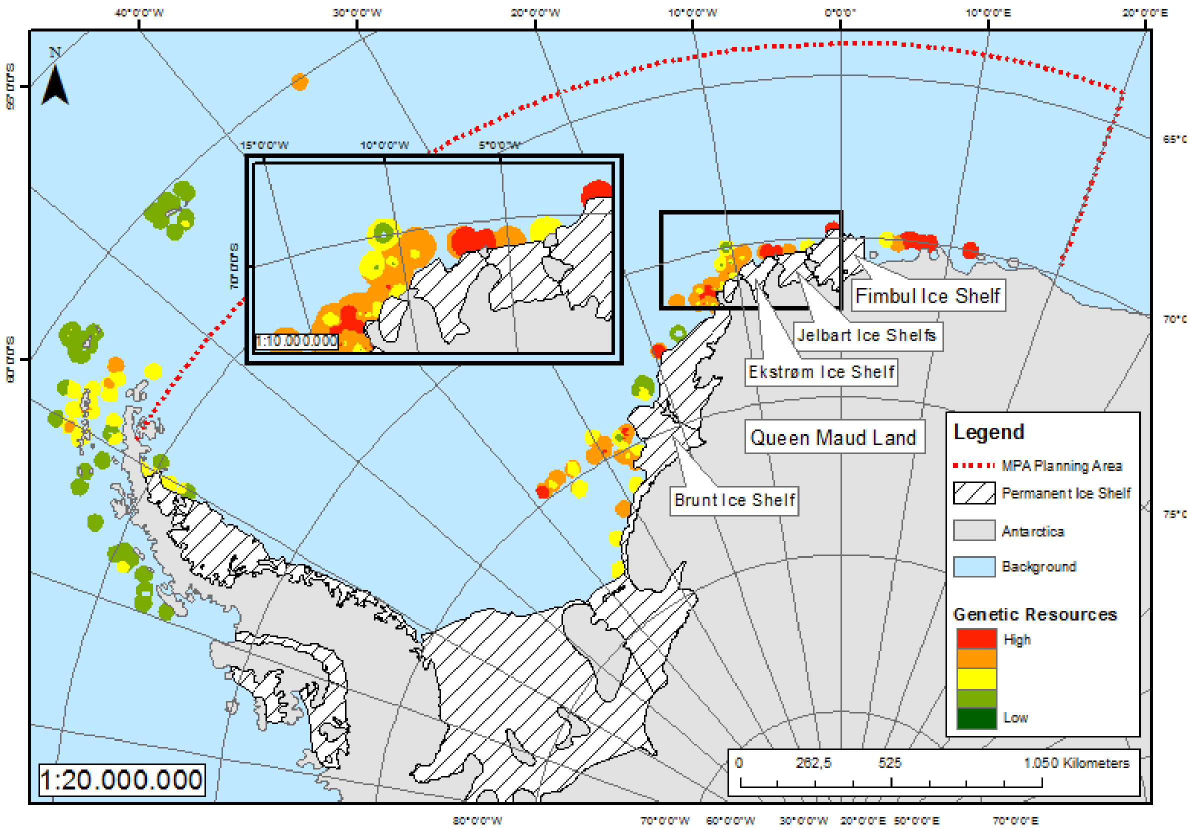


Figure 4 Spatial distribution of genetic resources in the Weddell Sea study area smoothed with IDW. Red indicates areas with high supply and green indicates low supply. The legends were classified on the basis of the data's overall standard deviation. The lower limit of the scale is the overall minimum value of the data, whereas the upper limit of the scale is the overall maximum value.

Carbon sequestration

Overall, in most parts of the study area, carbon sequestration was relatively low (mean chl *a* concentration ≤ 0 5 mg/m^3) (Fig 5) Most of the carbon was sequestered within three general areas, which include areas north-west of George VI Ice Shelf, near Larsen C Ice Shelf, offshore Ronne Ice Shelf, and east of Filchner Ice Shelf northwards along the coast of Queen Maud Land. These results reflect well the chl *a* distribution published in Moore & Abbott (2000) and Teschke *et al*. (2015c).

Table 4 Summary statistics of log10-transformed chl *a* concentrations (in mg/m^3) for 1997 to 2010.

Parameter	Value
Mean	-0.29
StdDev	0.37
Sum	-84.00
Min	-1.30
Max	1.75
Range	3.05
Median	-0.40

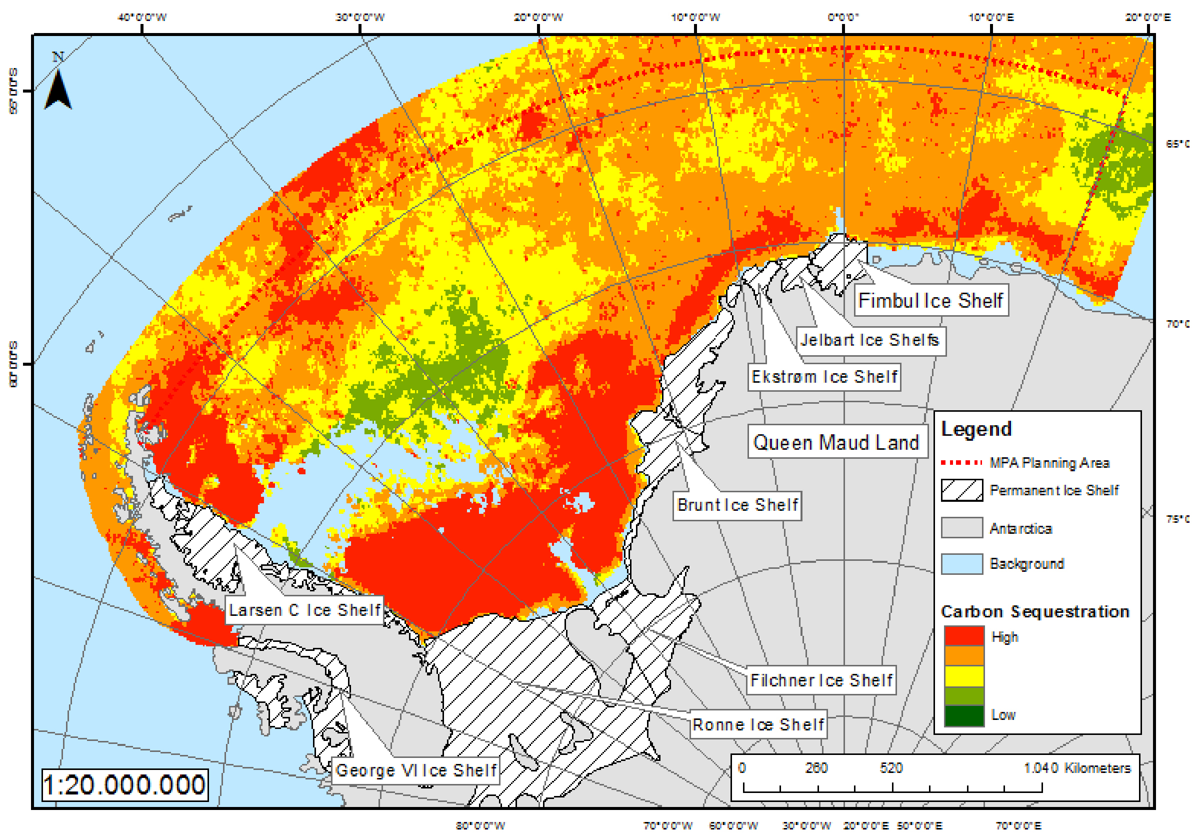


Figure 5 Spatial distribution of carbon sequestration (in mg/m^3) in the study area averaged for 1997-2010 (Nov-Mar). Red indicates areas with high supply and green indicates low supply of this service. Areas in background color north of Ronne-Filchner ice shelf had no valid chl *a* data because of heavy sea ice or persistent cloud cover. The legends were classified on the basis of the data's overall standard deviation. The lower limit of the scale is the overall minimum value of the data, whereas the upper limit of the scale is the overall maximum value.

Tourism

Tourism visitation

The landing sites in the Weddell Sea region received on average about 1200 tourists per season (see Table 5). No landing site showed more than 14130 visitors per season. There were large differences of the number of tourists among sites (StdDev = 2897). Sites at the northern tip of the Antarctic Peninsula were most popular (Fig. 8). Here, the provision of cultural services was highest at Cuverville Island, followed by Goudier Island, Whalers Bay, Neko Harbor and Half Moon Island.

The two tourist destinations in the eastern Weddell Sea, Atka Bay Rookery (Atka Iceport) and Novolazarevskaya Station, showed quite low tourism provision with an average of about 30 tourists per season (Fig. 8). Distinct variation was not only evident among different destinations but also within visits of individual sites over different seasons (Fig. 6, Fig. 7). Even Cuverville Island, the most visited site, experienced these variations. Its peak in visitation during the 2007/2008-season (about 20000 visitors) was followed by a steady decrease with a minimum in 2011/2012 with about 10000 visitors. In the following years, Cuverville Island was characterized by steadily increasing numbers of visitors with two peaks in 2012/2013 and 2013/2014 (Fig. 6).

Some sites were only sporadically stopped at and did not receive visitors for several seasons (see Appendix Table 10). This explains the quite large standard deviation in some cases (Fig 7; Appendix Table 10). Some places of interest no longer seem to be on the agenda of current tours, since they have not shown tourism activity for up to eight years (e.g. Dorian Bay, Intercurrence Island, Madder Cliffs and Patriot Hills) (see Appendix Table 10). The same low service provision applied to Novolazarevskaya Station, which from 11 seasons was only approached four times so far. Thus, it can be summarized that tourism was only found at the Antarctic Peninsula.

Table 5 Summary statistics of the number of tourists per site in the study area from 2003-2014.

Parameter	Value
Mean	1265.71
StdDev	2897.02
Sum	146821.82
Min	0.0
Max	14129.63
N	116.0
CV	2.29
Range	14129.64
Median	78.41

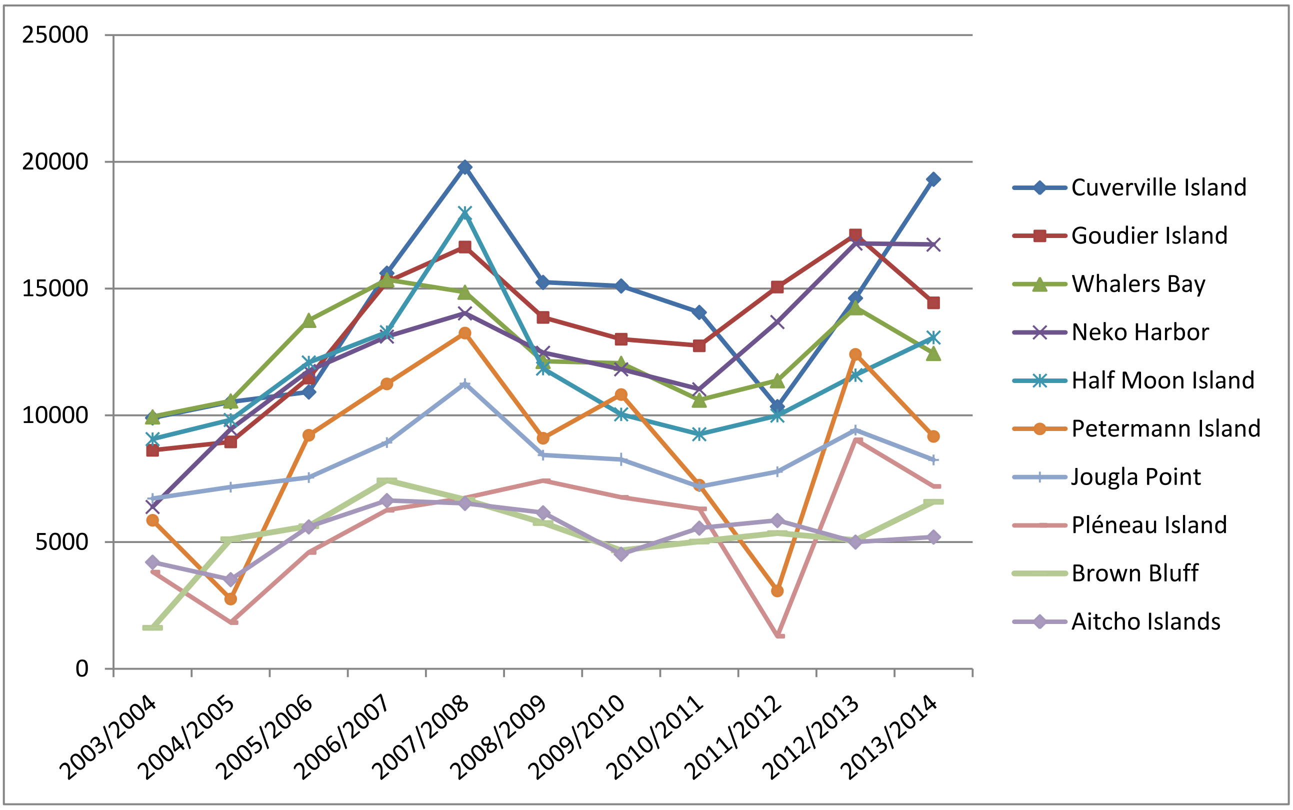


Figure 6 Number of tourists per season for the ten most visited destinations. The items in the legend are listed in decreasing order of mean tourist numbers. A table with all the destinations can be found in the Appendix (Table 10).

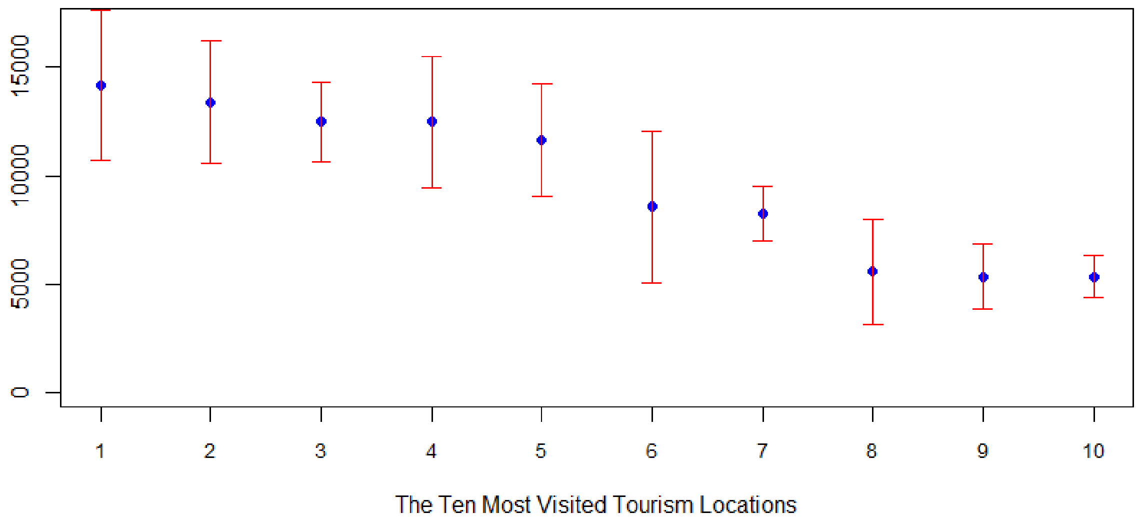


Figure 7 Mean and Standard Deviation of the ten most visited places in the study area. Blue indicates the mean from the 2003/2004 to the 2013/2014 season. Red indicates the StdDev. (1 = Cuverville Island, 2 = Goudier Island, 3 = Whalers Bay, 4 = Neko Harbor, 5 = Half Moon Island, 6 = Petermann Island, 7 = Jougla Point, 8 = Pléneau Island, 9 = Brown Bluff, 10 = Aitcho Islands)

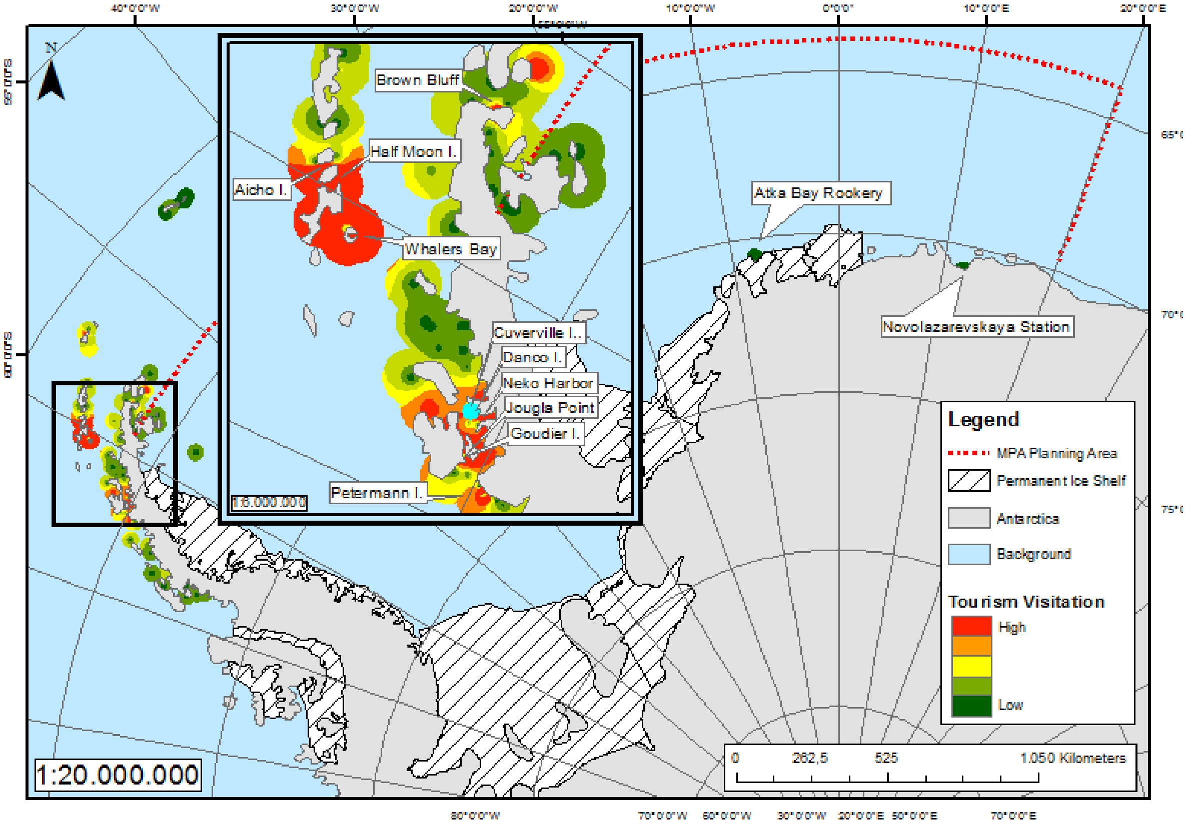


Figure 8 Spatial distribution of tourism visitation in the Weddell Sea study area smoothed with IDW. Red indicates areas of high tourism visitation; blue indicates areas of low visitation. The labels in the magnification window locate some of the ten most visited areas. The legends were classified on the basis of the data's overall standard deviation. The lower limit of the scale is the overall minimum value of the data, whereas the upper limit of the scale is the overall maximum value.

Tourism ship traffic

The concentration of tourism visitation was reflected in the pattern of marine traffic (Fig.9) (Lynch *et al*., 2009). Marine traffic volume was largest in the Gerlache Strait, Errera Channel, Neumayer Channel, Peltier Channel, Lemaire Channel, and the Penola Strait regions (Lynch *et al*., 2009). Here, locations were traversed by a ship up to 169 times per season between 2003 and 2008 (Table 6).

Table 6 Summary statistics of touristic shipping traffic, i.e. number of times that a location was traversed by a ship.

Parameter	Value (ship
Mean	0.15
StdDev	18.02
Sum	37275.05
Min	0.05
Max	169.00
N	3674.00
CV	1.78
Number of unique values	528
Range	168.95
Median	2.90

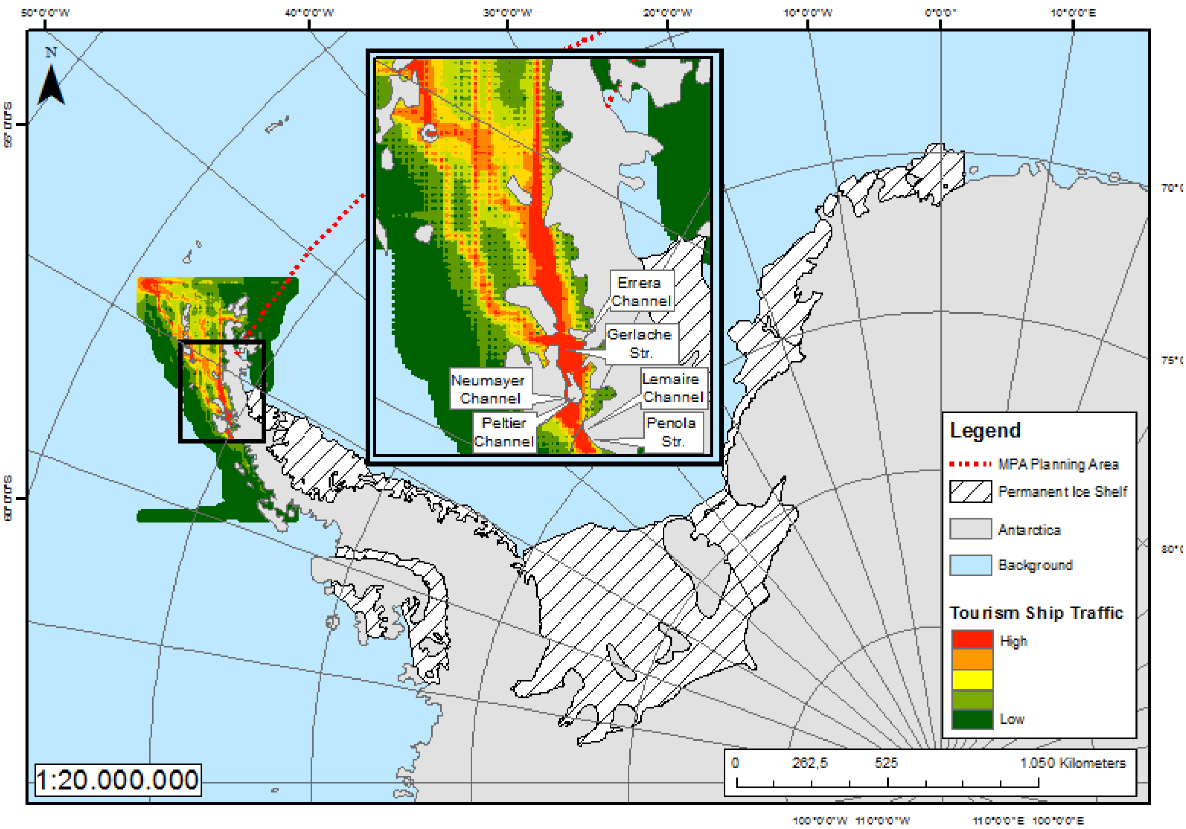


Figure 9 Spatial distribution of tourism ship traffic in the Weddell Sea study area smoothed with IDW. Red indicates areas with high volume of traffic and green indicates low volume of traffic. The labels in the magnification window locate the most traversed areas. The legends were classified on the basis of the data's overall standard deviation. The lower limit of the scale is the overall minimum value of the data, whereas the upper limit of the scale is the overall maximum value.

Hotspots and coldspots

Genetic resources

When it comes to hotspots and coldspots of genetic resources, there was a pronounced east-west division (Fig. 10). This was apparent in a gradient on the level of service provisioning, from high to lower occurrence of hotspots when moving westwards. At the Antarctic Peninsula there was a relatively low variety of benthic taxa (mean number of taxa = 11; results not shown), with some exceptions around South Shetland Islands and King George Island. In contrast, in the eastern part of the research area, along Queen Maud Land coast, the variety of higher benthic taxa was quite large (mean number of taxa = 19; results not shown). A similar distribution pattern was shown in areas further south, towards Ronne-Filchner Shelf Ice where quite a few hotspots of higher benthic taxa occurred (mean number of taxa = 17; results not shown). In addition, there was a high number of higher benthic taxa east of South Orkney Islands in the very north of the study area (mean number of taxa = 16; results not shown). In summary, hotspots of genetic resources made up about 1 % of the study area.

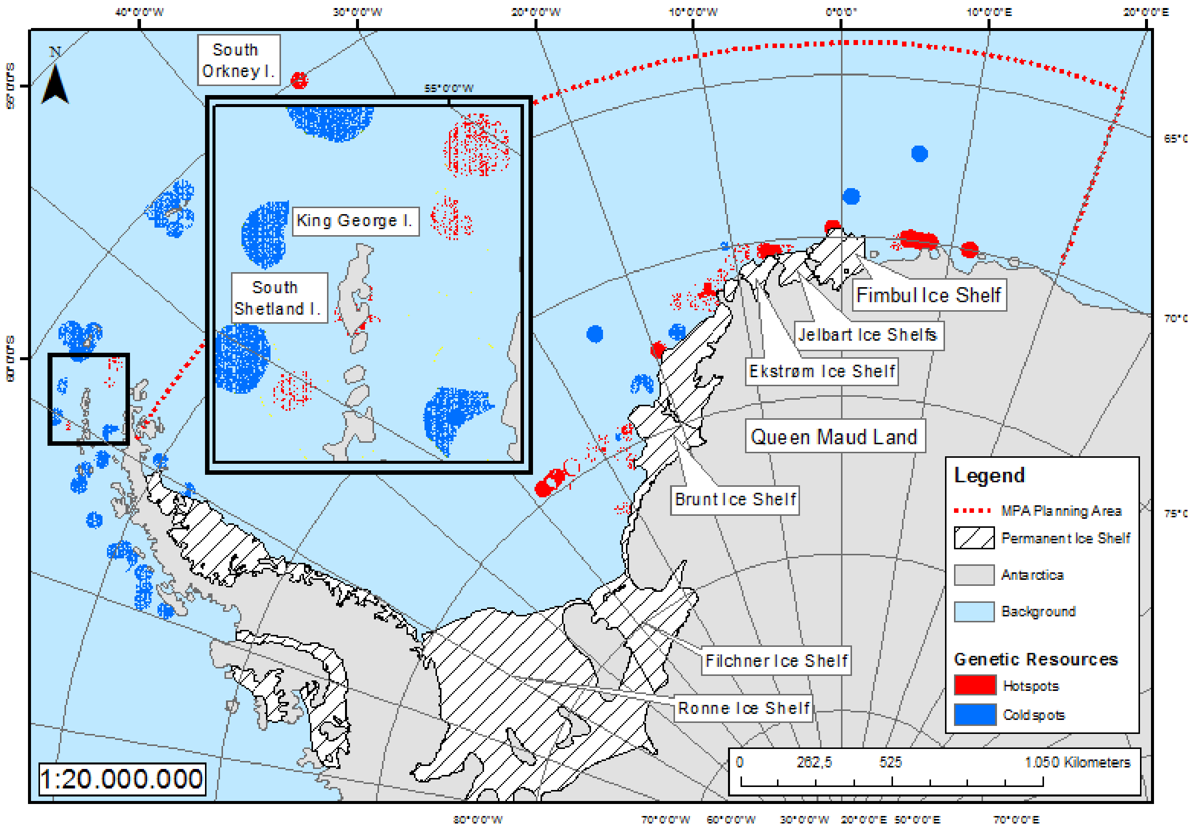


Figure 10 Hotspots and coldspots of genetic resources. Red indicates areas with genetic resources delivery in the upper 25th percentile and blue indicates areas with genetic resources provision in the lowest 25th percentile.

Carbon sequestration

Maximum values of carbon sequestration occurred in the coastal/shelf waters along the Antarctic Peninsula and the coast of Queen Maud Land (Fig. 11). High provisioning of the ES also occurred in the southern Weddell Sea. Service hotspots of carbon sequestration occurred over large portions of the study area (13.9 %).

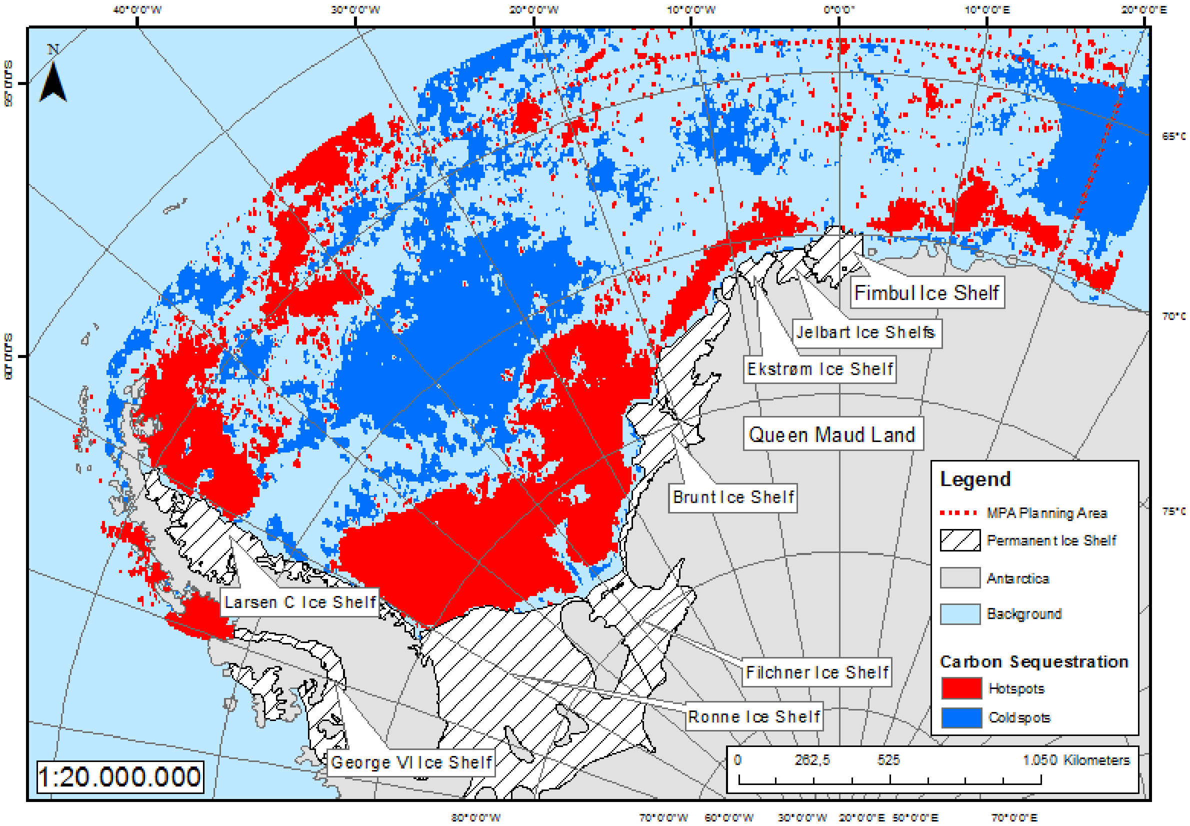


Figure 11 Hotspots and coldspots of carbon sequestration. Red indicates areas with carbon sequestration delivery in the upper 25th percentile and blue indicates areas with carbon sequestration in the lowest 25th percentile.

Tourism

Tourism visitation

Extensive tourism activity was observed in the northwestern sector of the study area, with Cuverville Island, Goudier Island, Whalers Bay, Neko Harbor, Half Moon Island and Petermann Island and Jougla Point being the regions generally providing services at the highest levels (Fig. 12). Service coldspots can be found in areas off the Western Antarctic Peninsula (WAP).

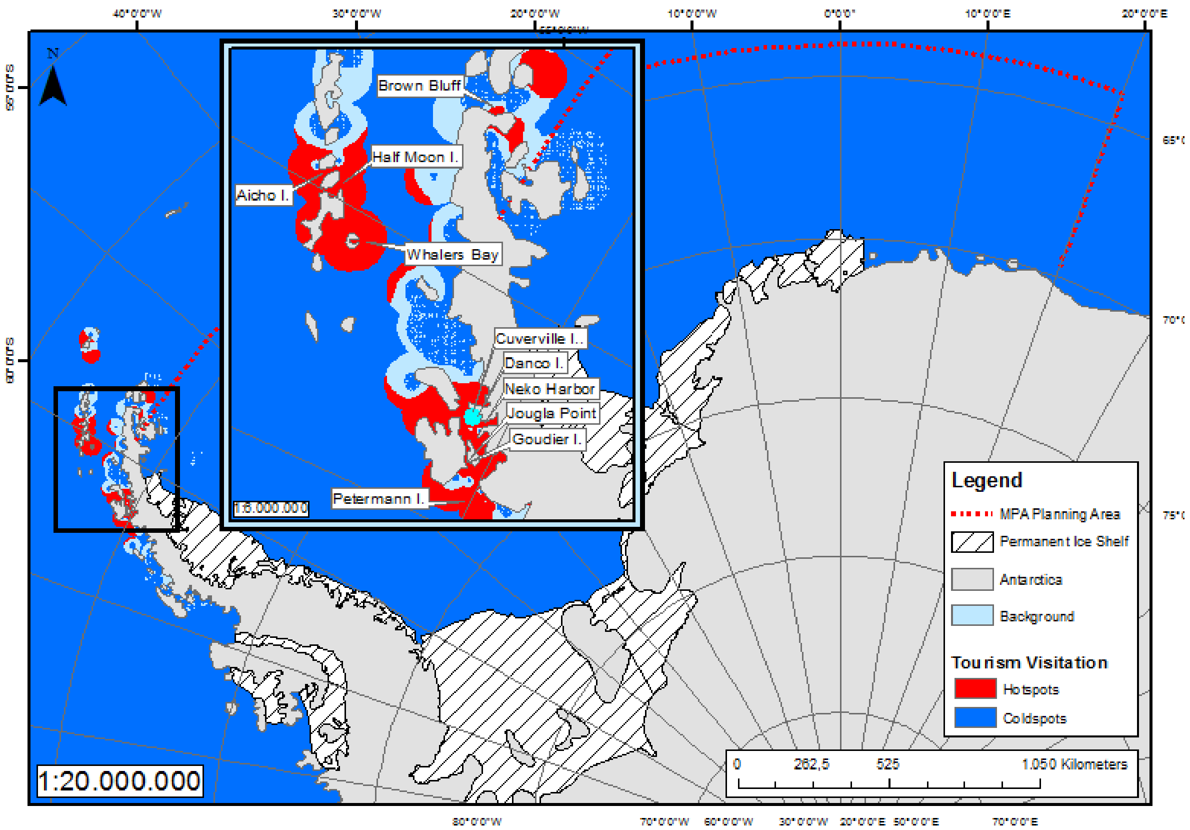


Figure 12 Hotspots and coldspots of tourism visitation. Red indicates areas with tourism delivery in the upper 25th percentile and blue indicates areas with tourism in the lowest 25th percentile.

Tourism ship traffic

Hotspots of marine traffic occurred from King George Island in the north towards Petermann Island in the south (Fig. 13). On their tours, ships traversed through Gerlache Strait, Errera Channel, Neumayer Channel, Peltier Channel, Lemaire Channel, and the Penola Strait regions to reach different islands of the Antarctic Peninsula (Lynch *et al.*, 2009).

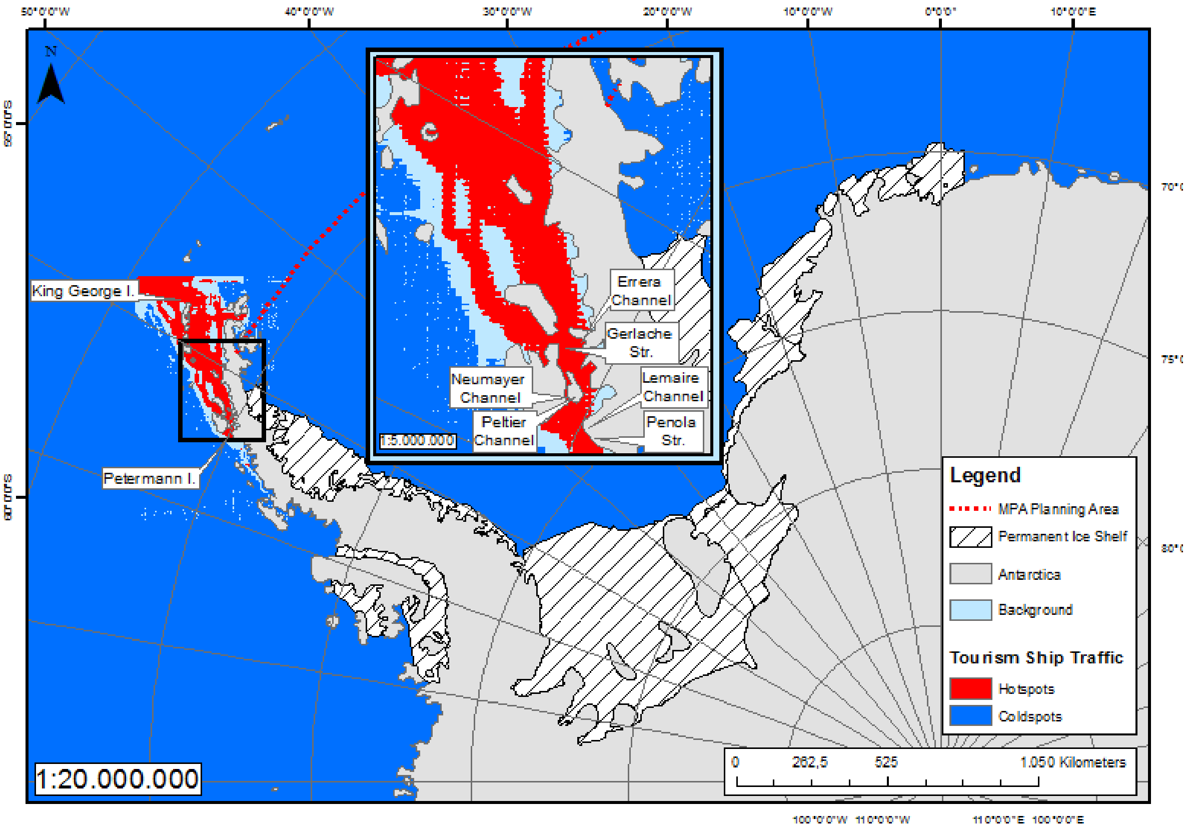


Figure 13 Hotspots and coldspots of tourism ship traffic. Red indicates areas with tourism ship traffic volume in the upper 25th percentile and blue indicates areas with tourism ship traffic volume in the lowest 25th percentile.

Tourism visitation and tourism ship traffic

The pattern emerging in Figure 14 indicates that the highest concentration of tourism was found at the WAP, with little tourism in areas off the Antarctic Peninsula.

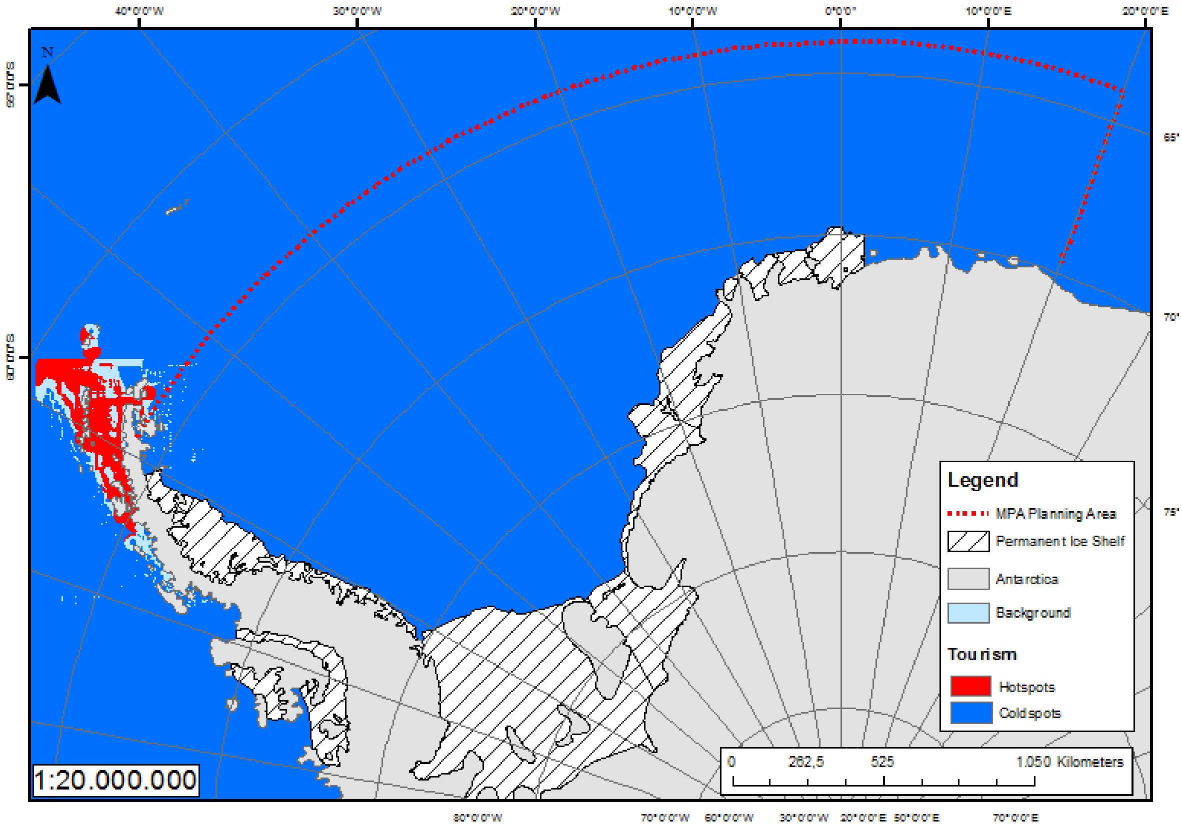


Figure 14 Hotspots and coldspots of tourism. Red indicates areas with tourism volume in the upper 25th percentile and blue indicates areas with tourism volume in the lowest 25th percentile.

Trade-offs and synergies between ES

Relationships between pairs of ES, and between individual ES and sea ice cover

Correlations between genetic resources, carbon sequestration and tourism were not significant except for the relationship between carbon sequestration and tourism ships ($r = -0.31$, $p < 0.05$) (Table 7, Fig. 15). This spatial concordance is of particular note for the first hypothesis (see section "Research Objective and ypotheses") A significant positive relationship existed within the ES tourism, i.e. between tourism visitation and tourism ships ($r = 0.32$, $p < 0.05$).

However, the most conspicuous values were related to the second hypothesis (see section "Research Objective and ypotheses"). There were significant moderate to strong negative correlations between sea ice cover in austral spring (Oct - Nov) and both parameters tourism and genetic resources, respectively (Table 8, Fig. 16). In the following months (Jan - Mar), correlations were no longer significant. The relationship between carbon sequestration and sea ice cover showed only a weak positive correlation. All the observations are statistically significant at the 99 % confidence level.

Table 7 Correlation coefficients (r) between pairs of ES; * = p value < 0.05.

	Tourism Visitation	Tourism Ships	Genetic Resources	Carbon Sequestration
Tourism Visitation	1.00	0.32*	0.19	0.03
Tourism Ship Traffic	0.32*	1.00	0.22	-0.31*
Genetic Resources	0.19	0.22	1.00	0.09
Carbon Sequestration	0.03	-0.31*	0.09	1.00

Table 8 Correlations coefficients (r) between individual ES and sea ice coverage; * = p value < 0.05.

	Tourism Visitation	Tourism Ships	Genetic Resources	Carbon Sequestration
Oct mean ice coverage	-0.25*	-0.47*	-0.41*	0.29
Nov mean ice coverage	-0.30*	-0.41*	-0.36*	0.30
Dec mean ice coverage	-0.12*	-0.21*	-0.03	0.40
Jan mean ice coverage	0.11	0.12	0.17	0.17
Feb mean ice coverage	0.16	0.19	0.36	0.16
Mar mean ice coverage	0.12	0.12	0.39	0.25

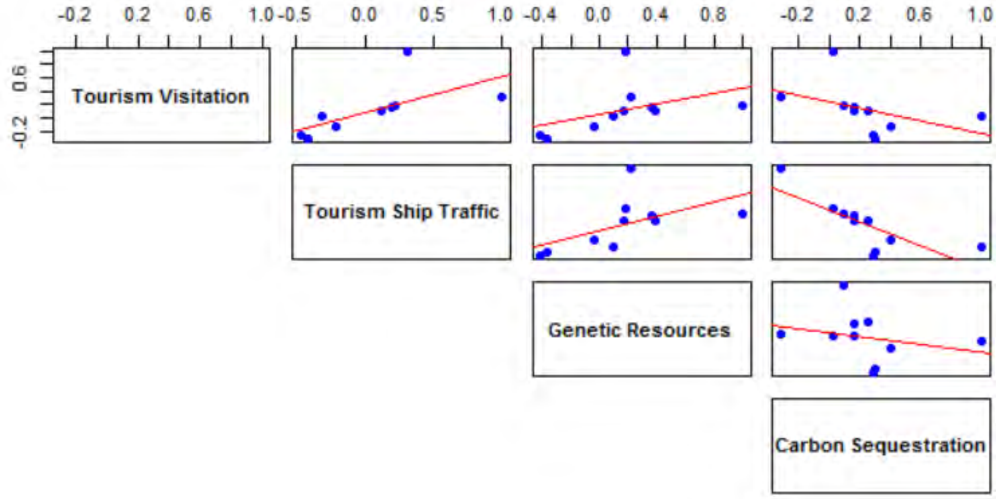


Figure 15 Scatter diagram of the relationships between ES, in particular between both tourism and genetic resources and carbon sequestration. The fitted linear line is indicated in red.

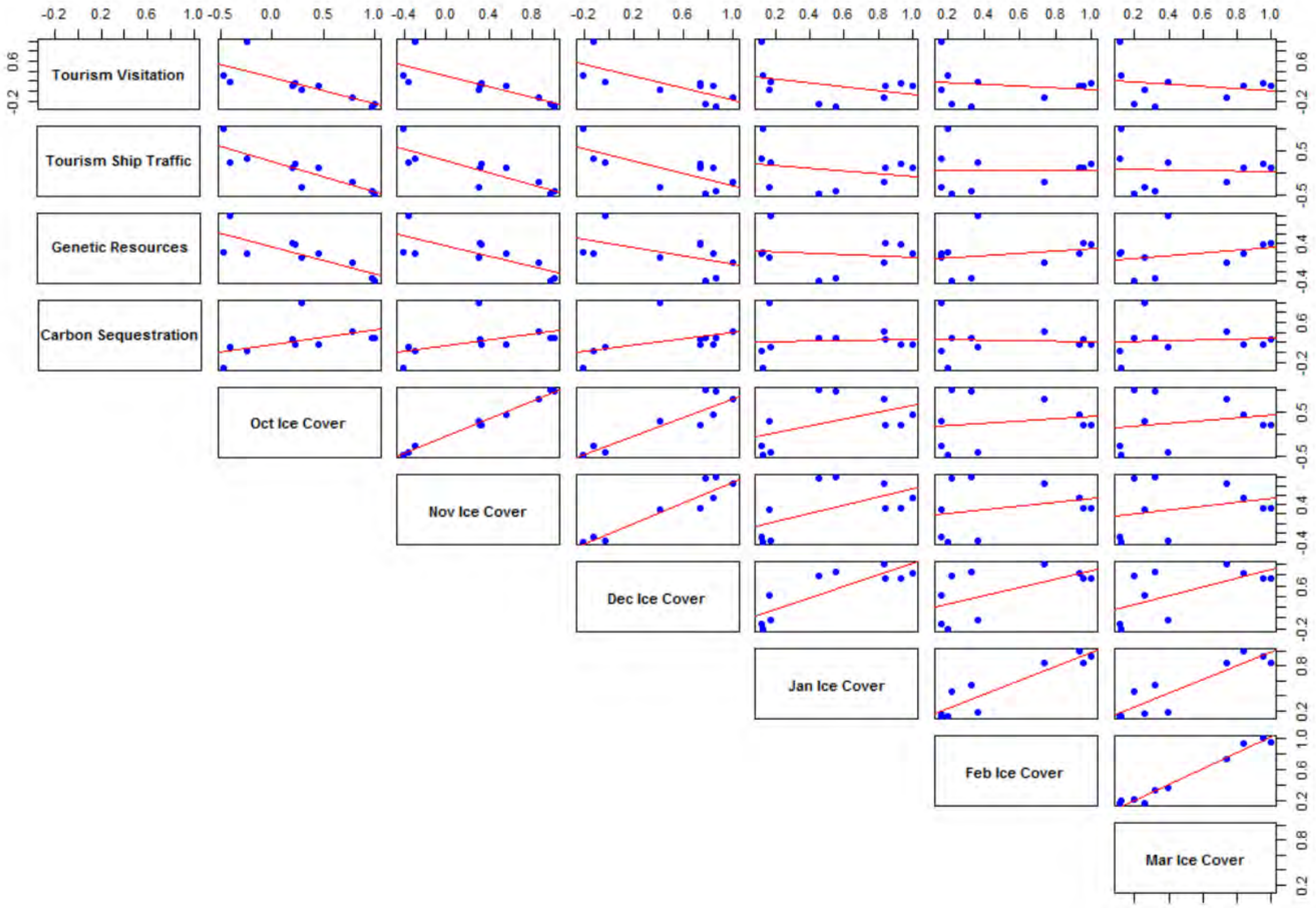


Figure 16 Scatter diagram of the relationships between ES and sea ice cover. The fitted linear line is indicated in red.

Relationships between hotspots and coldspots of ES

The ES hotspots and coldspots in the study area showed relatively weak correlations with each other and with no significant relationships (Tab. 9). There was only one significant correlation between hotspots of tourism and coldspots of tourism ($r = -0.75$, $p < 0.05$).

Nevertheless, there were areas where high values of multiple benefits coincide (i.e. super hotspots) (see Fig. 17). These regions are located around the Antarctic Peninsula (e.g. at Joinville Island) and along coasts of Queen Maud Land towards Ronne-Filchner Ice Shelf. However, these super hotspots represent a relatively small area of the study area (0.44 %). Yet, in large areas at least one service was provided to the highest level.

Even if coldspots of ES were spread all across the study area, only small locations showed low supply of all services (Fig. 18). Thus, super coldspots made up only very small fractions of the study area.

Table 9 Correlation coefficients between hotspots (HS) and coldspots (CS) of pairs of ES; * = p value < 0.05.

	Tourism HS	Genetic R. HS	Carbon S. HS	Tourism CS	Genetic R. CS	Carbon S. CS
Tourism HS	1.00	-0.19	-0.25	-0.75	-0.03	0.09
Genetic R. HS	-0.19	1.00	0.06	0.22	-0.37	0.10
Carbon S. HS	-0.25	0.06	1.00	0.33	-0.09	-0.28
Tourism CS	-0.75*	0.22	0.33	1.00	0.04	-0.25
Genetic R. CS	-0.03	-0.37	-0.09	0.04	1.00	-0.13
Carbon S. CS	0.09	0.10	-0.28	-0.25	-0.13	1.00

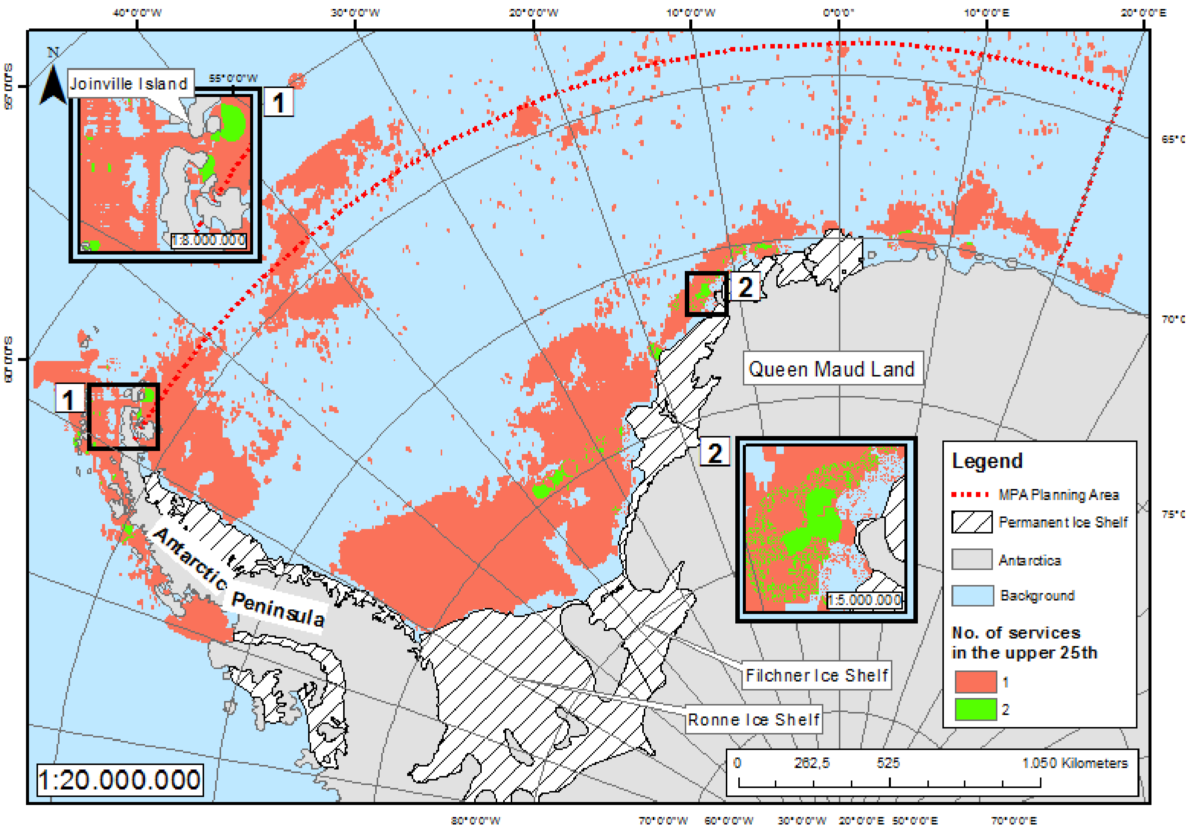


Figure 17 Map of super hotspots, i.e. hotspots for delivery of multiple ecosystem services. Red and green indicate the number of ES in the upper 25th percentile.

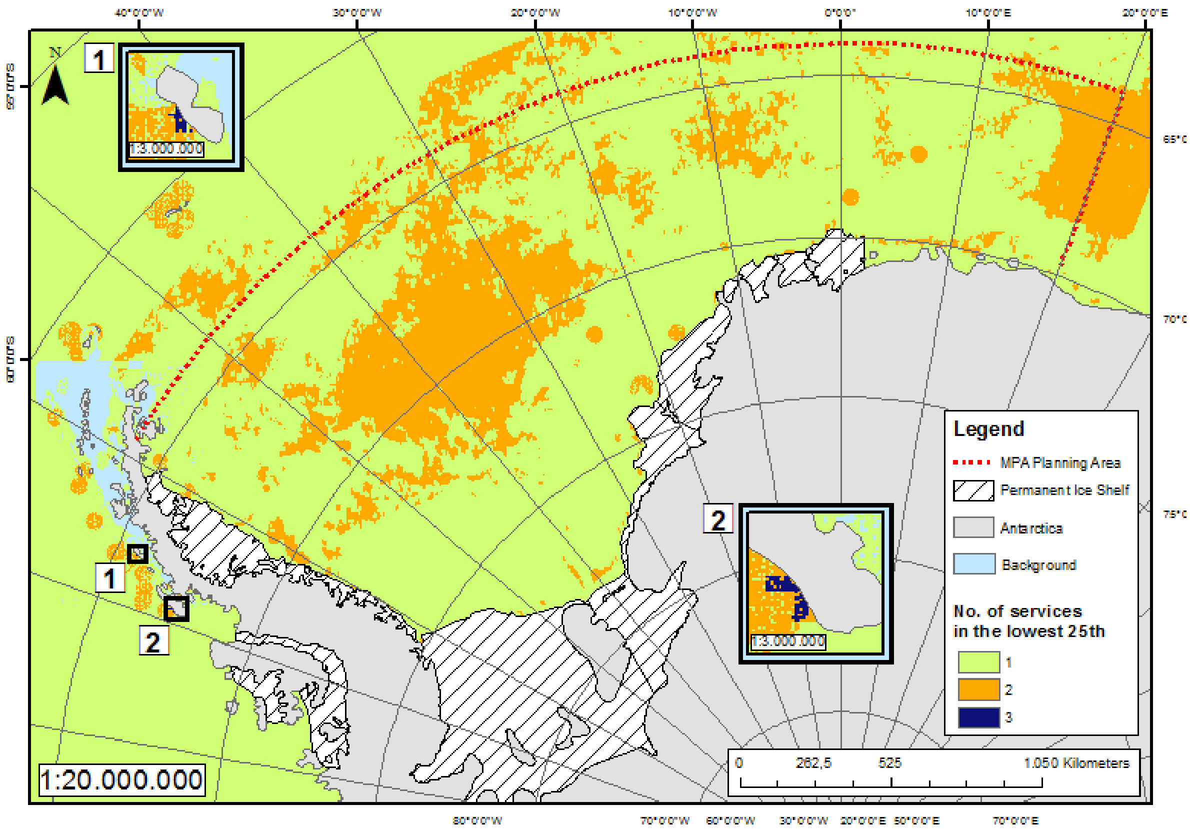


Figure 18 Map of super coldspots, i.e. coldspots for delivery of multiple ecosystem services. Light green, orange and purple indicate the number of ES in the lowest 25th percentile.

5. DISCUSSION

Major Findings

Chl *a* as basis of every ES

The outcome of the study is contrary to the first hypothesis claiming that, ultimately, the provision of all ES in the study correlates positively with chl *a* concentrations, i.e. carbon sequestration. The analyses show that this connection cannot be established. Tourism ship traffic is significantly negatively correlated with chl *a*. All the other ES showed neither a positive nor a negative significant correlation with chl *a*. These results can be explained by the fact that there is quite a long cascade of ecosystem components and functions between chl *a* and the other services. For instance, due to the complexity of marine ecosystems, the link from phytoplankton over krill and whales and other krill-feeding charismatic species to tourist numbers seems to be hidden or even distorted, maybe also by data availability. Still, this result is unexpected since Atkinson et al. (2004) and Grant *et al*. (2006) published evidence that chl *a* concentrations correlate positively with krill density, and not only ir ovi and ildebrand (2011) but also Thiele *et al*., (2000) uncovered the positive link between chl *a* and mammal occurrences. Nevertheless, it seems that the subsequent connections to tourism are more multidimensional and multifactorial than expected from previous literature. Previously, Flores (2009), Murphy *et al*. (2012) as well as Nicol and Raymond (2012) stated that Southern Ocean systems are far more complicated than often presumed from the relatively short trophic pathways.

The reason for the low correlations between the ES and chl *a* could also be that tourist activities do not only involve animal watching; there are more tourist attractions independent of chl *a*, i.e. spatially distributed, such as visiting the icecaps and glaciers of the islands and coasts (Oceanwide Expedition, 2015). Added to this is the potential temporal mismatch of phytoplankton bloom, target species occurrence and tourism visitation. Tourist vessels may enter the study area at the time when chl *a* concentrations are already decreasing but charismatic species are still present. Chl *a* concentration is a highly variable parameter, i.e. a closer look needs to be taken at the chl *a* values at the exact area of tourism hotspots, in the exact year and months of tourism activity. The spatial and temporal variation of chl *a* concentrations is hidden and disguised in the mean data used for the analyses which means that relationships to tourism and genetic resources may easily be distorted.

Ice as limiting Factor

The influence of sea ice cover on the provisioning of ES was mostly in line with the hypothesis. Significant negative correlations exists between tourism and ice cover from October to December (Table 8, Fig. 16). This is also true for genetic resources and sea ice cover. At this time, the Weddell Sea is covered by melting, but still thick, ice after an ice cover maximum in September (Teschke *et al*., 2015a). During November, sea ice cover is usually still close to the maximum winter extent, with a rapid decrease occurring during December and January (Moore and Abbott, 2000). The winter extent of sea ice compares to almost twice the size of Europe (Flores, 2009). It does not only have a direct negative effect on tourism through limitations with regard to accessibility, it also has indirect negative effects on the provision of this ES. This is because even though sea ice constitutes a habitat for seals, penguins and whales (Flores, 2009), marine mammals depend on ice free areas (”polynyas”) to breathe (e.g. Gill and Thiele 1997) and to reach open water (Zimmer *et al*. 2008). From December to March, there are no more significant adverse effects of ice cover on the provision of ES. This is due to the fact that during these times of austral summer, the research area is characterized by widespread ice-free conditions with a sea ice minimum in February (Teschke *et al*., 2015a).

The finding that tourism shows a strong negative correlation with ice conditions is supported by comparing the spatial occurrences of this ES with the pelagic regionalization of the Southern Ocean by Raymond (2011). Following this regionalization, more than half of the hotspots of tourism activity are located in areas subject to challenging sea ice conditions most of the year.

However, it should be noted that the large coldspots of tourism provision off the Antarctic Peninsula are also likely to be a consequence of the distance to coast. Most tours begin and end their journey from Ushuaia, Argentina (Lynch *et al*., 2009). Consequently, sites in the eastern part of the study area are too remote compared to the main sites that the Weddell Sea voyages visit.

In contrast to the clear relationship between ice and tourism, it is not clear why carbon sequestration shows only low correlations with sea ice cover ($r^2 \leq 0$ 16). Actually, chl *a* and sea ice are closely linked, with sea ice retreat leading to strong phytoplankton blooms (Flores, 2009; Moore and Abbott, 2000). The melting of sea ice enhances photosynthetic productivity not only due to the resulting stable stratification, but also as a consequence of the release of ice algae and nutrients from the melting ice (Flores, 2009). Chl *a* concentrations are not only spatially in close connection to ice, but also temporally. This can be seen by the fact that phytoplankton blooms develop as soon as the polynyas open up (Moore and Abbott, 2000). This would suggest that chl *a* concentrations correlate strongly with sea ice cover. A possible explanation for the fact that the opposite was observed might be that the correlations between chl *a* and sea ice cover were averaged as a result of the large spatial extent of the study area. To test this, the raster maps of carbon sequestration and sea ice cover were limited to a 200 km buffer around the permanent ice shelf. The objective was to only include the areas in the correlation analysis that are mainly exclusively subject to sea ice variations. After correlation analysis was performed with this setting, clear significant correlations between sea ice cover and carbon sequestration were revealed from October to and including January (see Appendix Table 11, Fig. 20). This underpins the argumentation explained above.

Spatial relationships between ES

The provisioning of ES is interlinked with positive and negative effects, i.e. trade-offs and synergies, between individual services. Ecosystem degradations tend to occur as simultaneous failures in multiple ES (Carpenter *et al*. 2006). These couplings have long been neglected, thereby overlooking wider consequences of decision making (Tallis and Polasky, 2009). This often resulted in policy failures (UNEP, 2011). In this study, hotspots of ES cover large portions of the study area (Fig. 17, red color indication). However, they were not spatially concordant, i.e. there was no significant spatial correlation (Fig. 17, green color indication; Table 9). The heterogeneity of services delivery, in combination with the low level of spatial congruence, suggests that the entire area is important for ES provision. This aligns with findings by Egoh *et al*. (2008). Even if in the course of this study only three services were assessed, its results imply that caution should be exercised when focusing conservation efforts on smaller areas. This agrees with conclusions drawn by Egoh *et al*. (2008). As already mentioned, the area is still in need of quantitative assessments to improve the data availability. Thus, present and future potential of service provisioning may easily be overlooked. Due to the weak correlations between the ES in the study area, it is not advisable to use one service to plan for other services (Egoh *et al*., 2008). Protecting a hotspot area of one service does not necessarily also enhance the provisioning of other services. This implies that conservation measures have to be conducted on a larger scale. Nevertheless, it is not clear from the study whether or not trade-offs or synergies could occur over time (Raudsepp-Hearne *et al.*, 2010). This is especially true in the light of the strong variability of some of the ES (e.g. carbons sequestration) and the large uncertainties with regard to the development of the two most important drivers of change in the study area: global warming and fishing.

Potential tourism

Tourism focuses mainly on occurrence of charismatic species such as whales (e.g. killer whales, humpback whales, minke whales) and penguins (e.g. Adélie penguins or Emperor penguins) (IAATO, 2015) (Fig. 19). This means that provision of the ES tourism is particularly high where these species occur and where they are accessible (Oceanwide Expeditions, 2015), i.e. where relatively manageable ice and weather conditions occur. Sea ice conditions, distance and harsh weather conditions are the reason why only relatively small areas (1.1%) have been identified as providing cultural services so far (Ghermandi *et al*., 2012). Nevertheless, even if the current provision of tourism is limited to few areas, it is likely that in future these services will increase their value and distribution due to global climate change (O'Donnol *et al*., 2011; Ghermandi *et al*., 2012). Surface air and seawater temperatures increased around the Western Antarctic Peninsula (WAP). As a consequence, glaciers on the WAP and nearby islands retreated. Additionally, the annual period of sea ice cover shortened (e.g. Stammerjohn *et al*., 2008; Turner *et al*., 2005; Whitehouse *et al*., 2008). This is very likely to lead to a temporal and spatial increase in tourism activity around the Peninsula region. This trend is already recognizable with tourism season starting earlier and ending later than ten years ago (Lynch *et al*., 2009). Figure 19 illustrates potential future tourism activity based on spatial distribution patterns of target species of sightseeing trips.

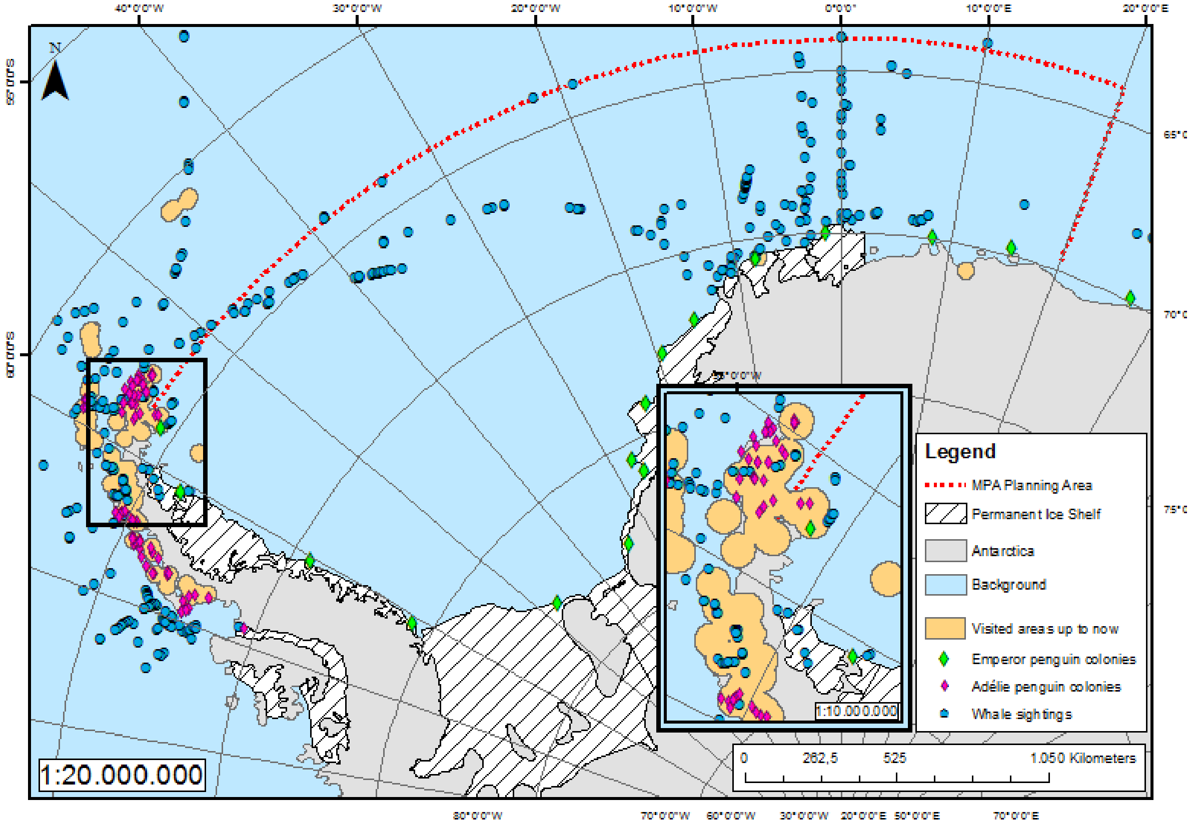


Figure 19 Map showing the current touristic areas, and the current distribution of penguin breeding colonies and whale sightings. The current distribution of penguin breeding colonies and whale sightings can be used as rough proxy for potential future tourism activity.

Methodological Issues

Selected Proxies

Looking at the ES mapping approach applied, several points worth discussing emerge. One major issue refers to questions related to the selected proxies. ES are the result of numerous ecosystem functions (Austen *et al*., 2011) making the assessment and quantification of ES a comprehensive and complicated matter. This is further complicated given that the relationship between services, underlying ecosystem functions and biodiversity remains poorly understood (Barbier, 2007; Kremen, 2005). The matter becomes even more challenging in low-data regions like the study area. Added to this is that many marine species are mobile and different locations may be more or less important at different times (Hattam *et al*., 2015). Ideally, this dynamic is represented by the selected proxies (Hattam *et al*., 2015). The procedure to capture the ES genetic resources by using higher benthic taxa occurrence is a simplifying approach. It leads to an underestimation of the genetic variation in the region. This is why the resources assessed by this study should be complemented by data on other taxa distribution. Nevertheless, the results of this study offer valuable information on the biodiversity of the region if one is aware of the limitations.

It is also important to note that data on ship traffic volume was only available for the Antarctic Peninsula region. These circumstances are the reason why coldspots of ship traffic east of the Antarctic Peninsula were derived from the fact that this region does not receive high numbers of tourists. Therefore it is assumed that high volumes of tourism related ship traffic are very unlikely in this region.

In addition to this, satellite data in the study area underestimate in situ chl *a* values (Peck *et al*., 2010). The discrepancy is largest close to the coastline, also along the Antarctic Peninsula (Peck *et al*., 2010), i.e. areas where tourism abundance is biggest. This can add to the weakening of the relationships between chl *a* and the ES, and between chl *a* and sea ice cover. However, in the light of the enormous expanse and remoteness of the study area, satellite data is still reasonable for use, especially at offshore locations (Peck *et al*., 2010).

Thresholds for hotspots and coldspots

There is an ongoing debate within the ES research community on the threshold for defining ES hotspots and coldspots. Up to now, the classification methodology is stated quite arbitrarily in literature. Furthermore, Egoth *et al*. (2008) mention the lack of published thresholds in the literature. Cut-off points for hotspots range from the top 10 % to 30 % of service provision (e.g. Anderson *et al*., 2009; Locatelli *et al*., 2014; Qiu and Turner, 2013). Different thresholds lead to different results, and thus to different priorities for conservation planners. This is due to the fact that hotspot areas are often considered as areas where payoff from safeguard measures would be greatest, i.e. hotspots are a common measure to prioritize areas for biodiversity conservation (Egoh *et al*., 2008; Myers *et al*., 2000). They are often considered to be an opportunity for ecosystem conservation with limited resources and efforts (Egoh *et al*., 2008). Therefore, keeping the variation of thresholds in mind is very important when comparing different studies.

Cluster analysis

For the analysis of the multivariate data, a cluster analysis was performed by partitioning the data into meaningful subgroups or clusters (Fraley and Raftery, 1998). The cluster analysis divided the study area into clusters based on similarities regarding ice cover and ice thickness, similar to the pelagic clustering in Raymond (2011) and Teschke *et al*. (2015c). Then, differences in the provision of ES could be related to these sub-regions. The number of clusters was determined by Ward's method (Ward, 1963) Ward's method groups the data on basis of minimum variance. However, in view of the considerable amounts of data to be handled, a large amount of points have been involved in the analysis, even if the data sets were adjusted for NAs. A possible solution to the problem could be to use a k-means algorithm first to reduce the data to a certain number of clusters before applying other clustering procedures. Possibly, this could be the subject of future research.

Strengths and Limitations of the Study

One major shortcoming of this study is the spatial mismatch between data of different ES indicators. This irregular data coverage is likely to bias the results. The limitations in each of the data sources are recognized. The strength of the study rests on the comprehensive use of data available for the study area, on the consistent agreement with other studies both with regard to methodology and results (e.g. Galparsoro *et al*., 2014; Grant *et al*., 2013; Locatelli *et al*., 2014; Lynch *et al*., 2009; Teschke *et al*., 2015a, 2015b, 2015c) and on being a milestone in implementing the ES concept to this research area. Since the characterization of sets of ES has emerged only recently (Schröter *et al*., 2005), the current analyses may serve as a model example for mapping other marine regions. This is especially important in the light of a general lack of quantitative evidence available (UNEP, 2011). The results also open up the possibility to contribute to existing strategies, such as the planned MPA in the Weddell Sea. This is particularly important since this study bridges the gap between the natural sciences and the social sciences.

Further research on the topic in the study area may focus either on (i) the assessment of additional ES, (ii) more information on the relationships between the assessed ES (see Locatelli *et al*., 2014), or (iii) estimating their economic value. The latter is especially important to align economic forces with conservation (Daily *et al*., 2009) and to underpin that the large-scale losses of ES in the marine system (Costanza *et al*., 2014) also lead to negative economic effects. A possible tool for the economic valuation of the services provided is the Integrated Valuation of Ecosystem Services and Tradeoffs tool (InVEST). The tool is an integrated approach to inform planners about the impacts of alternative resource management choices on the economy, human well-being, and the environment (Daily *et al*., 2009).

6. CONCLUSION

To examine trade-offs and synergies between genetic resources, carbon sequestration and tourism, correlation analyses were conducted. The quantification and mapping of benefits revealed that interactions of ES occur in characteristic patterns with trade-offs between tourism and carbon sequestration. Even though the results were not in complete agreement with the hypothesis, they showed some degree of interaction between the ES. The strongest relationship, however, was between the ES and sea ice cover. Here, tourism showed the clearest response. Even if the correlations between carbon sequestration and sea ice cover were not significant in the main analyses, this changed as soon as the study area was limited to areas closer to the sea ice zone. Further research, especially on the effects of different biological, ecological and physical features on growth and bloom of phytoplankton is needed to overcome those methodological constraints.

In addition, it has been shown that ecosystems of the Weddell Sea region are important on a global and long-term scale. This is demonstrated by the seasonally high capacity to sequestrate carbon, and by the earlier mentioned role of providing a place of refuge for ice dependent, pelagic key ecosystem components. Another important aspect is the potential of the area to deliver tourism in the near future. However, latter development has the potential to turn into a threat for the region if it is not well managed (Teschke *et al*., 2015a; Shah, 2013).

The lack of data calls for cautiousness in relation to the large undiscovered potential of the Weddell Sea ecosystems to provide benefits in the future, e.g. genetic resources. Looking ahead, due to progressing climate change effects, even more uncertainties arise, e.g. relating to the way climate processes affect the structure and dynamics of Southern Ocean ecosystems and how they will respond to these changes (Murphy *et al*., 2012; Teschke *et al*., 2015a). Management measures should integrate these uncertainties in their decision making which is a call for the protection of the Weddell Sea region. This would clearly be in line with the precautionary philosophy of CCAMLR.

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8. APPENDIX

Table 10 List of all the destinations in the Weddell Sea study area. Data according to IAATO.

station	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	mean	stdev
Cuverville Island	9901	10523	10921	15607	19790	15244	15102	14061	10344	14621	19312	14129,64	3450,05
Goudier Island	8621	8954	11472	15266	16640	13863	13004	12744	15062	17115	14438	13379,91	2806,07
Whalers Bay	9941	10570	13749	15347	14858	12128	12054	10601	11368	14248	12444	12482,55	1837,91
Neko Harbor	6387	9452	11749	13107	14023	12470	11816	11029	13681	16775	16733	12474,73	3002,09
Half Moon Island	9064	9819	12086	13281	17984	11844	10040	9256	9990	11585	13070	11638,09	2571,87
Petermann Island	5862	2756	9215	11241	13247	9098	10822	7248	3074	12406	9169	8558,00	3506,23
Jougla Point	6721	7169	7547	8927	11252	8431	8260	7188	7776	9419	8242	8266,55	1273,58
Pléneau Island	3818	1825	4592	6258	6739	7422	6767	6312	1290	9039	7198	5569,09	2414,68
Brown Bluff	1621	5116	5629	7434	6674	5752	4675	5023	5357	5075	6592	5358,91	1499,19
Aitcho Islands	4208	3520	5600	6639	6529	6156	4521	5551	5851	5002	5200	5343,36	976,65
Danco Island	702	1910	2762	3655	3634	2959	4040	3016	4700	8198	6981	3868,82	2142,30
Skontorp Cove	2007	1757	2800	5602	5613	4635	3752	4634	316	5311	5335	3796,55	1819,21
Paulet Island	1365	3611	4507	5561	4978	7814	2529	3614	5414	118	615	3647,82	2340,24
Telefon Bay	1351	1510	2184	3252	3068	3049	2269	2862	3622	3800	4510	2861,55	965,67
Point Wild	2056	2556	4457	3489	3087	3363	2699	1966	559	1965	3769	2724,18	1073,94
Hannah Point	4246	3873	5601	94	2039	2678	1681	1689	2716	2209	2188	2637,64	1480,93
Melchior Islands	2111	1684	2694	3800	5258	2847	3263	3657	144	1788	1738	2634,91	1364,94
Yankee Harbor	3026	1872	2521	3273	3987	2072	1863	1704	1081	2238	3736	2488,45	911,66
Baily Head	1843	1294	3504	2279	1937	1989	1886	1354	1533	2332	3206	2105,18	704,16
Pendulum Cove	2014	2389	4093	4021	1893	2337	1873	1109	678	809	533	1977,18	1219,19
Devil Island	277	1992	2370	2809	925	2852	2056	1268	1314	86	273	1474,73	1013,02
Yalour Islands	1357	585	1361	2564	1235	1536	1191	920	328	1670	2688	1403,18	722,72
Gibbs Island	156	0	128	0	2157	2575	5841	3791	69	149	376	1385,64	1971,33
Penguin Island	2311	1419	1724	1480	2189	1737	1288	93	651	943	516	1304,64	696,41
Enterprise Island	331	1649	1454	1528	1843	1317	636	953	263	1762	2347	1280,27	661,34
Argentine Islands	1627	930	1111	1822	1450	1544	1118	296	467	475	1190	1093,64	509,25
Detaille Island	731	0	155	754	1071	1402	1512	1587	0	2371	1465	1004,36	756,04
Gourdin Island	242	1009	575	506	548	1261	996	236	494	1222	2318	855,18	605,57
Portal Point	703	551	690	609	598	893	425	707	878	1813	1501	851,64	425,80
Cape Lookout	494	1425	1083	656	376	686	1016	320	325	491	1119	726,45	376,60
Torgersen Island	657	738	763	613	786	228	959	736	336	853	416	644,09	227,06
Fish Islands	264	111	703	514	1133	1138	1270	751	195	259	617	632,27	410,41
Astrolabe Island	439	368	694	353	594	806	301	1678	192	1043	220	608,00	441,58
Useful Island	0	335	146	805	751	1083	718	1597	55	412	549	586,45	477,01
Hydrurga Rocks	495	328	424	270	442	509	616	83	689	1168	949	543,00	306,97
Orne Islands	172	661	679	697	1010	451	140	1317	177	268	149	520,09	392,54
Horseshoe Island	207	323	0	261	337	1020	981	556	174	465	812	466,91	338,90
Prospect Point	593	0	265	526	738	591	285	960	131	600	168	441,55	292,59
Stonington Island	92	98	0	330	450	1153	1027	582	0	339	756	438,82	402,57
Robert Point	462	129	302	1074	380	270	319	120	153	344	748	391,00	287,71
Turret Point	105	253	414	141	994	273	96	326	196	741	713	386,55	299,44
Shingle Cove	881	307	282	1014	92	346	431	109	137	0	0	327,18	338,41
Georges Point	624	0	0	694	153	365	78	13	165	464	546	282,00	264,53

Hovgaard Island	153	7	124	141	183	96	233	1431	191	194	242	272,27	389,96
Spigot Peak	255	805	512	327	131	195	239	47	222	138	21	262,91	224,74
Snow Hill Island	58	1150	520	0	276	284	0	16	375	0	89	251,64	347,18
Rosamel Island	68	681	0	0	74	0	108	1327	0	143	91	226,55	413,60
Damoy Point	642	1292	0	0	0	0	0	0	0	0	0	175,82	417,30
Ardley Island	0	0	108	140	267	214	273	217	362	120	2	154,82	123,19
Wauwermans Islands	0	0	0	3	65	24	75	1345	67	0	8	144,27	399,38
Waddington Bay	229	0	100	220	430	117	93	12	92	116	89	136,18	120,03
Heroina Island	0	93	212	243	0	272	76	68	393	0	0	123,36	135,67
Union Glacier	0	0	0	0	0	0	0	275	0	682	263	110,91	217,86
Bongrain Point	0	0	0	0	110	175	0	180	127	226	396	110,36	128,52
Dorian Bay	417	694	0	0	0	0	0	0	0	0	0	101,00	233,09
Patriot Hills	0	188	0	200	253	282	161	0	0	0	0	98,55	117,46
Seymour Island	0	146	30	171	228	42	12	69	107	0	146	86,45	77,88
Penguin Point	0	0	126	172	181	0	0	49	384	0	0	82,91	123,48
D'Urville Monument	0	0	63	0	513	0	0	237	0	0	0	73,91	162,24
Intercurrence Island	0	42	0	51	668	0	0	0	0	0	0	69,18	199,48
Cape Valentine	0	0	199	70	0	0	335	0	0	0	111	65,00	110,71
Christiania Islands	87	53	0	79	4	53	50	52	45	240	39	63,82	64,03
Crystal Hill	93	255	90	49	0	0	0	0	197	0	0	62,18	89,69
Duthiers Point	0	0	234	0	411	0	0	0	5	9	6	60,45	135,51
View Point	0	214	84	0	0	45	0	138	0	86	0	51,55	72,17
Cape Tuxen	82	5	10	0	5	269	8	24	0	110	14	47,91	81,81
Madder Cliffs	94	317	0	0	0	0	0	0	0	0	0	37,36	96,94
Berthelot Islands	0	0	0	366	0	0	0	0	0	36	0	36,55	109,80
Novolazarevskaya (Novo) station	0	0	0	0	0	0	52	88	0	127	97	33,09	48,93
Girard Bay	0	5	0	0	9	44	53	228	0	10	0	31,73	67,72
Charcot, Port	323	0	0	0	0	0	0	0	0	0	0	29,36	97,39
Atka Bay Rookery (Atka Iceport)	0	206	0	0	0	0	0	101	0	0	0	27,91	66,38
Danger Islands	43	0	143	42	0	0	0	0	0	35	0	23,91	43,59
Camp Point	108	5	0	0	143	0	0	0	0	0	0	23,27	51,17
Fildes Peninsula	133	0	0	0	0	0	0	0	0	67	19	19,91	42,64
Blaiklock Island	0	0	0	0	4	0	72	64	77	0	0	19,73	33,08
Jonassen Island	0	0	0	0	0	0	57	106	0	0	0	14,82	34,74
Mount Demaria	17	0	19	19	13	9	22	0	1	25	17	12,91	9,09
Pitt Islands	0	0	28	8	8	23	18	0	5	29	22	12,82	11,44
Alcock Island	0	96	0	34	0	0	0	0	0	0	0	11,82	29,72
Cape Kinnes	0	79	0	0	0	0	0	0	0	0	48	11,55	26,61
Murray Island	0	0	0	2	92	11	0	0	0	5	10	10,91	27,21
Suárez Glacier	96	0	0	0	0	0	0	0	0	0	0	8,73	28,95
Mount Mill	0	0	3	9	24	9	21	2	7	0	7	7,45	8,24
Heywood Island	0	0	0	0	0	0	0	0	80	0	0	7,27	24,12
Barcroft Islands	0	50	0	0	0	0	0	0	0	6	0	5,09	15,00
Palaver Point	0	0	0	0	0	0	0	0	5	10	29	4,00	8,89
Duthoit Point	0	33	0	0	0	0	0	0	0	0	0	3,00	9,95
Bennett Islands	0	0	0	0	0	12	0	0	5	0	0	1,55	3,78

Wiggins Glacier	0	0	0	0	0	0	0	0	0	16	0	1,45	4,82
Challenger Island	0	7	0	0	0	0	0	0	0	0	8	1,36	3,04
Cape Evensen	0	0	0	6	0	0	0	0	0	3	0	0,82	1,94
Spring Point	0	0	0	0	0	0	0	0	0	0	6	0,55	1,81
Macaroni Point	0	0	2	0	0	0	0	0	0	0	0	0,18	0,60
Arago Glacier	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cape Dubouzet	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cape Dundas	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cape Gage	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cape Kjellman	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cape Melville	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Comb Ridge	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Cormorant Island	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Gaston Islands	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Gin Cove	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Gosling Islands	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Heim Glacier	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Huemul Island	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Lagarrigue Cove	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Martin, Point	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Metchnikoff Point	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Pitt Point	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Port Lockroy	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Port Lockroy	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Rongé Island	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Rum Cove	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00
Small Island	0	0	0	0	0	0	0	0	0	0	0	0,00	0,00

Table 11 Correlations coefficients (r) between individual ES and ice coverage after the raster maps of carbon sequestration and sea ice cover were limited to a 200 km buffer around the permanent shelf ice; * = p value < 0.05.

	Tourism Visitation	Tourism Ships	Genetic Resources	Carbon Sequestration
Oct mean ice coverage	-0.52*	-0.80*	-0.32*	0.64*
Nov mean ice coverage	-0.58*	-0.74*	-0.29*	0.63*
Dec mean ice coverage	-0.55*	-0.71*	-0.27*	0.59*
Jan mean ice coverage	-0.55*	-0.50*	-0.11	0.38*
Feb mean ice coverage	-0.28*	-0.18	0.14	-0.04
Mar mean ice coverage	-0,18	-0,13	0,13	-0,07

Figure 20 Scatter diagram of the relationships between ES, and between individual ES and sea ice cover after the raster maps of carbon sequestration and sea ice cover were limited to a 200 km buffer around the permanent shelf ice. The fitted linear line is indicated as red line.