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Review

# The application of remote sensing for marine protected area management

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ABSTRACT

Marine protected areas (MPAs) are important tools for the conservation of marine biodiversity but their designation and effective monitoring require frequent, comprehensive, reliable data. We aim to show that remote sensing (RS), as demonstrated for terrestrial protected areas, has the potential to provide key information to support MPA management. We review existing literature on the use of RS to monitor biodiversity surrogates, e.g. ecological (e.g., primary productivity) and oceanographic (e.g., Sea Surface Temperature) parameters that have been shown to structure marine biodiversity. We then highlight the potential for RS to inform marine habitat mapping and monitoring, and discuss how RS can be used to track anthropogenic activities and its impacts on biodiversity in MPAs. Reasons for low integration of RS in MPA management and current limitations are also presented. This work concludes that RS shows great promise to support wildlife managers in their efforts to protect marine biodiversity around the world, in particular when such information is used in conjunction with data from field surveys.



**Contents**



## 1. Introduction

Marine biodiversity is under serious threat from anthropogenic stressors, such as fisheries (Worm et al., 2009), pollution from land-sources (Klemas, 2011a) and increasingly from climate change (Greene et al., 2010; IPCC, 2011; Valdes et al., 2009) and ocean acidification (Hoegh-Guldberg et al., 2007). Yet marine biodiversity is key to the provision of many ecosystem services: marine resources were recently estimated to contribute 16.9% of the animal protein for nutrition worldwide (FAO, 2012). Apart from the intrinsic biodiversity value, there are economic arguments for the protection of marine biodiversity (Balmford et al., 2002; Costanza et al., 1997). Habitats such as mangroves are key for coastal protection against extreme flooding events (Costanza et al., 1997; Dahdouh-Guebas, 2006). High marine biodiversity moreover increases the resilience of marine ecosystems against climate change and ocean acidification (Hughes et al., 2007; Wilson et al., 2009). This makes

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the maintenance of marine biodiversity a significant environmental management objective.

Marine protected areas (MPAs) are important tools in the conservation of marine biodiversity (Worm et al., 2009). They can be broadly defined as spatial protection measures associated with varying access and resource use limitations, ranging from gear restrictions to no-take zones (Roberts, 2005). The IUCN defines a MPA as "*any area of intertidal or sub-tidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment*" (Kelleher, 1999). While 13.9% of the terrestrial environment is under protection (Chape et al., 2008), recent calculations by the Marine Reserve Coalition show that only 3.2% of the marine environment is (Marine Reserves Coalition, 2012) – the proportion of this that is effectively protected, is likely to be much lower. This figure falls short of the 10% coverage target to be achieved by 2012 that was internationally agreed under the Convention on Biological Diversity (CBD) in 2006 (Annex IV, Target 1.1, CBD, 2006). It should be noted, that in 2010 the time-frame was revised to 10% coverage by 2020 (Strategic Goal C, Target 11 CBD, 2010), although up to 30% have been called for (Sheppard et al., 2012). Most existing MPAs are located in the coastal zone and in order to realistically reach the 10% target it will be necessary to extend the designation of MPAs to the pelagic realm. Within national Exclusive Economic Zones (EEZs) there are a few recently established MPAs that incorporate the pelagic realm, such as the no-take marine reserve in the British Indian Ocean Territories (Sheppard et al., 2012). Outside of EEZs, however, the status of the High Seas under the United Nations Convention on the Law of the Seas as areas beyond national jurisdiction makes it complicated to establish, manage and enforce MPAs (Druel et al., 2011), with the notable exception of some initiatives by regional organisations, e.g. the multinational conservation organisation responsible for the North East Atlantic (OSPAR) (O'Leary et al., 2012). Meanwhile political progress is being made (Chiarolla et al., 2012); the recent Rio + 20 outcome document specifically requests an international framework for the designation of MPAs outside national jurisdiction to be developed before 2014 (Doran et al., 2012). MPAs have been the subject of intense scientific discussions and improvement of current practices has been suggested by taking into consideration issues including, but not limited to: difficulty of enforcement (Mora and Costello, 2006); indirect trophic effects on species (Fenberg et al., 2012); limited effect on highly migratory species (Hyrenbach et al., 2000; Roberts, 2000); representativeness (Boersma and Parrish, 1999; Fraschetti et al., 2008; Stevens, 2002); capacity for self-recruitment/larvae retention (Bell, 2012; Mora and Costello, 2006); vulnerability to land-based pollution (Boersma and Parrish, 1999); and being inadequate to address detrimental effects of climate-change (Selig et al., 2012). Scientific guidelines for MPA designation are not yet routinely implemented (Rabaut et al., 2009), nor is there an agreed set of criteria for site selection. The ecological criteria reviewed by Salm and Price (1995) are similar to the ones adopted by OSPAR in 2003 (O'Leary et al., 2012) and the indicators for Ecologically and Biologically Significant Areas (EBSAs) (Dunn, 2011; Gregr et al., 2012) adopted by CBD in 2009 (see Appendix, Table 1A). Balancing ecological criteria with social, economic and political considerations is an important aspect of decision making, resulting in a bias towards well studied sites, where strong pro-conservation arguments can be provided (O'Leary et al., 2012) with low opposition by stakeholders (Roberts, 2000). Once designated, being able to monitor a given MPA using scientifically sound criteria and protocols is key in demonstrating MPA effectiveness (Fenberg et al., 2012). While terrestrial and marine ecosystems are obviously different, some of the challenges faced by managers are of a similar nature, e.g. the difficulties associated with the monitoring of large, remote areas without high field data coverage. In particular, as MPAs are being more frequently established in the pelagic realm to increase global representativeness, the issue of designating and monitoring large areas using scattered, selective in situ datasets will become more frequent (O'Leary et al., 2012). It is therefore important to explore whether lessons can be learnt from terrestrial protected area management to inform MPA management.

Remote sensing (RS) has been advocated as being key in supporting the designation, mapping, and monitoring of terrestrial protected areas (Gross et al., 2009; Pettorelli et al., 2012). RS offers repeatable, standardised and verifiable information on long-term trends in ecosystem structure and processes at the global scale (Muller-Karger et al., 2005). RS has been applied successfully to address a variety of questions relevant to environmental management, including, but not limited to: landscape change monitoring (Townsend et al., 2009); habitat indicator derivation (Bommel et al., 2005), representativeness assessment (Armenteras et al., 2003); connectivity monitoring (DeFries et al., 2005); and climate change impact analysis (Pettorelli et al., 2012). There have been numerous notable recent reviews and books on the applications of RS for coastal managers (Klemas, 2011a; Miller et al., 2005; Weng, 2010), coastal biodiversity indicators (Strand et al., 2007), mangrove ecosystems (Kuenzer et al., 2011), seagrass meadows (Dekker et al., 2006; Kirkman, 1996), reef fish management (Hamel and Andréfouët, 2010) and fisheries science (Klemas, 2012). To date, however, there has been no review on the merits and pitfalls of using RS to inform the designation, mapping, monitoring and management of MPAs for biodiversity protection, especially in regions with low in situ data availability. With this review, we aim to fill this gap in knowledge, by providing an overview of the opportunities associated with the use of RS to inform the management of MPAs. This review will start by providing a brief presentation of the physical and biological parameters structuring marine environments and relevant to marine biodiversity assessments that can be derived from RS. The use of RS information to map marine habitats will then be explored, followed by a discussion on the monitoring capabilities of RS to detect and map anthropogenic threats and their potential impacts on biodiversity in MPAs. The review will end by listing existing limitations and highlighting new RS developments relevant to MPA management.

## 2. Remote sensing to monitor environmental correlates of biodiversity in MPAs

Biological diversity, or biodiversity, refers to the "*diversity within species, between species and of ecosystems*" (CBD, 1992). RS is the derivation of information by analysing radiation received by a sensor. For an explanation of RS terms, see Text 1A in the appendix. The direct observation of individual species is usually not possible using RS information, but biological and physical parameters that are reported to structure biodiversity patterns can be derived from RS data. Table 1 provides an overview of the most important parameters discussed below, as well as examples of satellite sources.

The monitoring of primary productivity to support terrestrial protected area management has been highlighted as a key tool by many (see e.g., Pettorelli et al., 2009, 2012; Pfeifer et al., 2011). In pelagic environments, primary productivity refers to the productivity of phytoplankton, which has a specific spectral signature due to its chlorophyll a content. The concentration can be inferred from ocean colour, i.e., from the radiation reflected back from the ocean in the visible wavelengths (Muller-Karger et al., 2005). The lessons from terrestrial PA management in this context, however, need to be interpreted with caution, as major differences exist in the importance of primary producers in the terrestrial and marine environments. Primary producers represent the basis of the food

**Table 1**
Examples of RS products (listed in the sensor and satellite column) that can be used to monitor marine habitats and environmental correlates of biodiversity (listed in the parameter column) in MPAs. Examples of published studies making use of such products for various purposes relevant to biodiversity monitoring in marine environments are also provided. This table is based on modified information extracted from Mumby et al., 2004; Brown et al., 2005; Klemas, 2011a. *Abbreviations*: SST, Sea Surface Temperature; SWV, Surface Wind Vector; SSH, Sea Surface Height; SSS, Sea Surface Salinity.

| Parameter | Sensor and Satellite | Dates of operation | Spatial resolution (m) | Swath (km) | Repeat viewing frequency (days) | References | Freely available |
|---|---|---|---|---|---|---|---|
| Bathymetry, ocean colour | IKONOS | 10/1999–present | 4 | 13 | 1–3 | Elvidge et al. (2004), Knudby et al. (2011), Purkis and Riegl (2005), Rowlands et al. (2008), Scopélitis et al. (2010) | No |
| Bathymetry, ocean colour | Quickbird | 10/2001–present | 4 | 22 | <3 | Knudby et al., 2011, Phinn et al. (2012), Rowlands et al. (2008), Rowlands et al., 2012, Scopélitis et al. (2010) | No |
| Bathymetry, ocean colour, SST | TM: Landsat 4–5 | 06/1982–12/1993, 03/1994–present | 30 | 170 | 16 | Knudby et al. (2011), Yamano and Tamura (2004) | Yes |
| Bathymetry, SSH | RA2:Envisat | 04/2003–04/2012 | NA | NA | 35 | Palacios et al. (2006), Petersen et al. (2008) | Yes |
| Bathymetry, SSH, SWV | SAR: ERS-1/ERS-2 | 08/1991–03/2000; 05/1995–09/2011 | 50.000 | 500 | 3/35/336 | Palacios et al. (2006), Petersen et al. (2008) | Yes |
| Ocean colour | SeaWIFS: OrbView 2 | 08/1997–12/2010 | 1100 | 2806 | 1–2 | Hardman-Mountford et al. (2008), Irwin and Finkel (2008), Palacios et al. (2006), Qiu et al. (2011), Sequeira et al. (2012), Valavanis et al. (2008), Wingfield et al. (2011) | Yes |
| Ocean colour, SST | AVHRR/1-3: NOAA/6-17 | 10/1978–present | 1100 | 2800 | 1 | Bogazzi et al. (2005), Maynard (2008), Palacios et al. (2006), Valavanis et al. (2008), Wingfield et al. (2011) | Yes |
| Ocean colour, SST | MODIS: Aqua | 05/2002–present | 1000 | 2330 | 16 | Druon (2010), Irwin and Finkel (2008), Queiroz et al. (2012), Valavanis et al. (2008) | Yes |
| Ocean colour, SST | ETM+: Landsat 7 | 04/1999–present | 30 | 185 | 16 | Arias-González et al. (2011), Mellin et al. (2012) | Yes |
| SSS | SAC-D: Aquarius | 06/2011–present | 150.000 | NA | NA | NA | Yes |
| SWV | Seawinds: Quikscat | 07/1999–11/2009 | 25.000/12.500 | 1800 | 1 | Risien and Chelton (2008), Valavanis et al. (2008), Wingfield et al. (2011) | Yes |

chain in both terrestrial and marine habitats, but in marine systems the standing biomass is often dominated by higher trophic levels (e.g., in pristine coral reefs (Sandin et al., 2008) or in the Antarctic benthos (Brey and Gerdes, 1997)). Moreover, phytoplankton does not provide substrate or habitat for other species as plants do in terrestrial habitats. Highly productive areas could therefore be expected to be less associated with high species richness compared to terrestrial ecosystems. Nevertheless, areas of high primary productivity have been shown to be highly correlated with benthic community patterns (e.g., Patagonian scallop; Bogazzi et al., 2005), and the distribution of highly migratory marine species (e.g., blue shark (Queiroz et al., 2012); bluefin tuna (Druon, 2010); whale sharks (Sequeira et al., 2012); and seabirds (Petersen et al., 2008)). These reported correlations indicate that the monitoring of primary productivity has a high potential to indirectly inform species distribution and therefore MPA establishment and management.

Temperature is another key parameter for understanding the distribution of biodiversity in terrestrial environments (Walther et al., 2002) and the same is true for marine ecosystems (Gregr et al., 2012; Tittensor et al., 2010). Sea Surface Temperature (SST) represents the temperature at the boundary between air and water, and can be derived by near-infrared sensors. Higher SST has been shown to be positively correlated with species diversity for several taxonomic groups (Tittensor et al., 2010). SST variability has also been shown to correlate with phytoplankton dynamics (Campbell and Wynne, 2011) and the spatial distribution of fish stocks (Lehodey et al., 2006). The relative patterns of SST inside a MPA can thus potentially inform the distribution of species richness in the area.

Wind patterns are seldom thought of being a monitoring priority by terrestrial PA managers, yet currents are among the most important oceanographic features to structure the pelagic environment (Dearden and Topelko, 2005). They can be monitored using radar scatterometers, as the backscatter can be used to analyse the surface wind vector (SWV), to infer currents (Brown et al., 2005). In association with this, Sea Surface Height (SSH) is the large-scale topography of the ocean's surface and can be derived by a satellite based altimeter; this data can help identify large scale circulation patterns such as geostrophic currents (Purkis and Klemas, 2011). Space-borne altimeters can also be used in combination with vessel-based echo soundings to derive bathymetry maps (Becker et al., 2009). Monitoring of currents is key to understanding and predicting energy flows: for example, the magnitude of larval import and export are dependent on local current systems (Bogazzi et al., 2005), and these larval flows shape genetic connectivity between meta-populations, as well as the scale of larval retention inside a MPA. This type of information could be especially important in the designation process of MPAs (Bell, 2012). Fronts - defined as sharp boundaries between two adjacent bodies of water – are another oceanographic feature influencing biodiversity patterns in the marine environment. Fronts have been reported to be areas of high primary productivity (Hardman-Mountford et al., 2008) and to be related to specific benthic communities (see e.g., Bogazzi et al., 2005; Wingfield et al., 2011) and apex predator site fidelity (Queiroz et al., 2012). Radar scatterometers are generally used to map oceanic fronts. Like SST, the detection and monitoring of fronts can be used as a proxy for the distribution of specific communities when no other data is available.

## 3. Remote sensing to monitor habitats in MPAs

"Habitat" is a key concept in ecology, being defined as the "(. . .) *type of site where an organism or population naturally occurs*" (CBD, 1992). Using RS to monitor habitats is routinely performed in terrestrial environments (Lengyel et al., 2008), and habitat distribution represents one of the most common information reported by Parties to the CBD.

The idea of structuring the pelagic environment into habitats has recently received increased attention (see e.g., Hobday et al., 2011; Chollett et al., 2012). Primary productivity, SST, currents and front patterns are all important parameters structuring the spatio-temporal distribution of marine biodiversity (Hardman-Mountford et al., 2008; Palacios et al., 2006; Valavanis et al., 2008; Wingfield et al., 2011) and can be used for habitat classification (Fraschetti et al., 2008; Gregr et al., 2012; see also Table 1). Importantly, a designation or monitoring system for MPAs based on such information could address the lack of representativeness that has been frequently cited as a limitation in current MPAs and the development of MPA networks (Klemas, 2011a; Stevens, 2002).

Coastal ocean is defined by Muller-Karger et al. (2005) as "*extending from the coast seaward to the edge of the continental margin* (*approximately 500 m depth*)". Coastal waters can be distinguished based on how the spectral signature is influenced by the sea bed and turbidity: "Case 2" waters refers to waters where the spectral signature is influenced by the sea bed and by a high level of turbidity (which is often the case in coastal waters), while "Case 1" waters refers to open ocean (Doxaran et al., 2002; D'Sa and Miller, 2005). Mangrove forests are coastal habitats that provide important nursery habitat for terrestrial and marine fauna (Nagelkerken et al., 2008), offer coastal protection, wastewater treatment and count among the ecosystems with the highest economic value (Costanza et al., 1997). RS can be used to inform on the distribution, health, productivity, composition and biomass of mangrove forests, as reviewed by Kuenzer et al. (2011). Methods used are mainly optical RS, but radar-based methodologies can also be employed (see e.g., Cornforth et al., 2013). Seagrass meadows are also habitats specific to "Case 2" waters. Seagrasses are marine flowering plants, occupying tropical and temperate soft-sedimentary coastal waters and estuaries. As primary producers, seagrasses provide food; they also stabilise the seabed and, like mangroves, provide important nursery habitat for many species (Dekker et al., 2006; Short et al., 2007). RS can be used for accurate mapping and monitoring the extent of seagrass meadows (Dekker et al., 2006; Godet et al., 2009; Kirkman, 1996). Coral reefs finally represent another example of coastal habitats and numerous studies exist on the use of RS to map and monitor the extent of coral reefs, coral health (Kuchler et al., 1986; Mumby et al., 1997; Rowlands et al., 2012; Scopélitis et al., 2010), geomorphological features, ecological zonation, and reef-fish communities (Arias-González et al., 2011; Knudby et al., 2011; Mellin et al., 2009). Relevant work also includes studies using RS to help manage coral-reef fisheries (Hamel and Andréfouët, 2010). Large-scale coral mortality events known as coral bleaching can also be studied using RS, as the occurrence of these events is strongly correlated to SST anomalies (Maynard, 2008; Sheppard and Rayner, 2002). The global prediction of local coral bleaching for a given SST anomaly is, however, not straightforward, as the mortality threshold differs regionally, depending on coral species, their symbionts, environmental history and small-scale topography (Maynard, 2008). When it comes to monitoring coral bleaching, SST should therefore be used as an indicator for threats, and not as a way to quantify bleaching. Moderate resolution RS can be used to map bleaching events for large areas of mono-species patches (Yamano and Tamura, 2004). Successes have also been achieved using high-resolution ocean colour RS data (Elvidge et al., 2004; Rowlands et al., 2008), especially in combination with field surveys (Purkis and Riegl, 2005).

## 4. Remote sensing to assess the impacts of anthropogenic threats

Marine biodiversity is threatened by a variety of anthropogenic stressors that can be monitored using RS (see Table 2 for an

**Table 2**
Examples of RS products (listed in the sensor and satellite column) that can be used to assess the impacts of anthropogenic threats (such as land use change, oil spills or Illegal, Undeclared or Unreported (IUU) fishing) on MPAs. Parameter in this case refers in some case to the detection of the anthropogenic threat itself (e.g., ship detection) or to the detection of the impact of a given threat (e.g., the detection of increased suspended matter as a result of land use change). Examples of published studies discussing the use of such products for various marine habitats are also provided.

| Parameter | Sensor & satellite | Dates of operation | Spatial resolution (m) | Swath (km) | Repeat viewing frequency (days) | References | Freely available |
|---|---|---|---|---|---|---|---|
| Ocean colour (CDOM), suspended matter | MERIS: Envisat | 03/2002–04/2012 | 300–1200 | 1150 | 35 | Oney et al. (2011) | Yes |
| Oil spills | SeaWIFS: OrbView 2 | 08/1997–12/2010 | 1100 | 2806 | 1–2 | Brekke and Solberg (2005) | Yes |
| Oil spills | SAR: ERS-2 | 05/1995–09/2011 | 50.000 | 500 | 3,35, and 336 | Brekke and Solberg (2005) | Yes |
| Coastal land use & change, oil spills | Hyperion: EO-1 | 11/2001–present | 30 | 7.7 | 16 | Brekke and Solberg (2005), Mumby et al. (2004) | Yes |
| Coastal land use & change | IKONOS | 10/1999–present | 4 | 13 | 1–3 | Mumby et al. (2004) | No |
| Coastal land use & change | Quickbird | 10/2001–present | 4 | 22 | <3 | Mumby et al. (2004) | No |
| Ship detection, suspended matter | HRG: | 05/2002–present | 2.5, 5, and 10 | 60 | 2–3 | Corbane et al. (2008), Corbane et al., 2010, Doxaran et al. (2002) | No |

overview). Land-use change is still one of the most important drivers of biodiversity loss in terrestrial habitats (Sala et al., 2000). It also impacts marine environments as various components of terrestrial run-off can have adverse effects on marine biodiversity (Boersma and Parrish, 1999). In this respect, suspended particular matter (SPM) and coloured dissolved organic matter (CDOM) are examples of features highly relevant to the monitoring of coastal habitats that can be successfully monitored using RS. SPM is a variable related to the sediment load in the water. Due to its light attenuation, increased SPM has a negative effect on primary productivity (Doxaran et al., 2002); high SPM can be indicative of increased sedimentation rates, which can detrimentally affect mangroves (Nagelkerken et al., 2008) and seagrass health (Kirkman, 1996). SPM can furthermore serve as an indicator for land-based pollutants that cannot be detected by RS, e.g., heavy metals (Burrage et al., 2002). CDOM is another component of run-off, and refers to organic matter that originates from decomposing organic material. SPM and CDOM can be inferred from ocean colour data when ground calibration data is available (Muller-Karger et al., 2005). River discharges often carry sediments and the resulting plumes can be tracked using RS (Burrage et al., 2002; Donato and Klemas, 2001). The monitoring of SPM and CDOM therefore allows the assessment of the interactions between the coastal environment and the adjacent land; regular assessments of CDOM concentrations can for example provide relevant information for the monitoring of water quality (Oney et al., 2011).

Oil spills generally refer to incidental large-scale releases of oil from tankers or oil drilling platforms: a famous example of oil spills is the Exxon-Valdez spill in 1989, which had long ranging impacts on marine wildlife (Royer et al., 1990). Large oil spills such as the Exxon-Valdez one are infrequent, while small scale oil spills are much more common events occurring when tankers empty their billage tanks (Klemas, 2010). Oil spills can cause significant damage to marine biodiversity: such damages have been particularly well studied in marine mammals (Williams et al., 2011). Their effects can have long-term consequences for the health and functioning of many coastal environments, such as mangroves (Boersma and Parrish, 1999; Duke et al., 1997), as well as more widespread effects relating to plankton and thus other species up the food chain. The early detection, tracking and prediction of the spread of an oil spill are key for the design of effective counter-measures, as illustrated by the recent oil spill of the Deepwater Horizon rig in 2010 (Klemas, 2010). Various established RS based methods exist to detect oil spills and track their development, e.g., using synthetic aperture radar (SAR) or infrared sensors (Klemas, 2010; Ottaviani et al., 2012). The detection of oil spills relies on the different properties of water and oil in the absorption and emission of electromagnetic waves (Brekke and Solberg, 2005; Klemas, 2010). Hyperspectral data can also be used to discriminate hydrocarbons and track oil spills (Hörig et al., 2001). Interestingly, information collected by hyperspectral sensors could be used to improve the monitoring of plastic pollution, something that has not been done so far. However, hyperspectral sensors are currently mainly air-borne (and therefore costly), with the exception of the Hyperion sensor on the EO-1 Satellite.

Illegal, Undeclared or Unreported (IUU) fishing is another major threat to the successful implementation of MPAs (Game et al., 2009). Large predatory fish, often targeted by IUU fisheries, have declined in most parts of the ocean (Worm et al., 2009) yet hold important functional roles (Hughes et al., 2007; McCauley et al., 2010). They often represent one of the original management targets for MPAs (Aburto-Oropeza et al., 2011; Koldewey et al., 2010). To enforce spatial closures and other fisheries management policies most nations require fishing vessels to carry a vessel monitoring system (VMS). To elude the regulation, however, fishing vessels can turn-off their VMS. Combining RS information with data from

**Table 1A**
Indicators for ecologically and biologically significant areas (EBSAs) adopted by the Conference of the Parties of the Convention on Biological Diversity 2008 (COP9) in decision IX/20 Annex I + II ordered by potential for remote sensing (RS) to inform these indicators. Examples of RS data that can be used to inform the EBSAs indicators are also provided.

| Indicators for EBSAs | RS potential | Example |
|---|---|---|
| Biological productivity | High | Primary productivity |
| Biological diversity | High | Biodiversity surrogates |
| Uniqueness or rarity | High | Biodiversity surrogates, habitats |
| Naturalness | Medium | Anthropogenic impacts |
| Vulnerability, fragility, sensitivity, slow recovery | Medium | Anthropogenic impacts, habitats |
| Importance for threatened species and/or habitats | Medium | Habitats |
| Special importance for life history of species | Medium | Habitats |

**Table 2A**
Average costs of several data sets per km$^2$. Costs are here detailed as the sum of acquisition costs and pre-processing costs, the latter being indexed using pre-processing time estimates (modified from Rohmann and Monaco, 2005). These costs include ground-truthing, mobilisation and demobilisation costs; ship cost is assumed to be 30,000$/day. Depth limit means the maximal depth under ideal conditions where remote sensing information can be reliably used to inform MPA management.

| Platform | Source | Depth limit [m] | Estimated acquisition cost [/km$^2$] | Estimated pre-processing time [scene] |
|---|---|---|---|---|
| Satellite | Landsat | Max 27 m | 0.41$ | <1 day |
| Satellite | IKONOS | Max 27 m | 50$ | <1 day$ |
| Plane | LIDAR (low quality) | Max 46 m | 375$ | 1+ day |
| Plane | LIDAR (high quality) | Max 46 m | 2000$ | Less than 7 days |
| Ship | Sonar (multibeam), shallow | – | 5100$ | 17 days |
| Ship | Sonar (multibeam), deep | – | 300$ | 1 day |

active VMSs allows ships that have switched their VMS off to be detected, as high-resolution optical satellites can be used to detect vessels and monitor vessel movement (Corbane et al., 2010). Optical sensors are not the only type of sensor able to detect ships: SAR allows the detection of boats up to a size of 10–15 m (Brusch et al., 2011). This is especially useful for remote areas where enforcement of MPAs by patrol vessels is difficult.

## 5. Limitations and outlook

A major constraint to the use RS to support MPA management is that, with the exception of altimeters for coarse scale bathymetry (Smith, 1997), most RS methods can only derive information from the upper layer of the ocean. Space-borne optical sensors only penetrate the water to a maximum of 27 m under the best conditions (Rohmann and Monaco, 2005); air-borne sensors such as the bathymetric light detection and ranging (LIDAR) only up to 46 m (Rohmann and Monaco, 2005). RS data is also limited at shallow depths due to the light absorption properties of sea water. Processes occurring in the upper layer of the ocean are only part of what defines patterns in biodiversity. Using larval connectivity as an example, it can be argued that deeper currents can be of equal or greater importance to understanding larval distribution, as studies have shown that these organisms are not passive (Vermeij et al., 2010) and avoid the surface layer to minimise their displacement away from their spawning area (Bradford et al., 2005; Cowen et al., 2000). Although RS cannot, at present, provide much information about the deeper layers of the ocean, one shouldn't underestimate the importance of RS information currently available to MPA managers. The upper layer is indeed the most productive layer of the ocean, forming the primary base of the food chain. The extent to which the surface layer affects deeper water layers or the benthic ecosystem below is then related to the strength of the bentho–pelagic coupling (Corliss et al., 2009), to the existence and depth of a thermocline (Bogazzi et al., 2005) and to the local currents system. This therefore means that in some areas, knowing the behaviour of the upper layer has the potential to provide reliable information on the behaviour of the layers below.

The available spatial resolution of RS data can then be viewed as technical constraint, limiting the use of RS data to support MPA management in coastal habitats, as even air-borne high resolution sensors fail to capture the complexity of key habitats such as coral reefs (Purkis and Klemas, 2011). Air-borne LIDAR holds great promise for high-resolution bathymetry for better habitat classification (Klemas, 2011b) and predicting fish communities (Knudby et al., 2011). The availability of high spatial resolution satellite data is increasing and will continue to increase, but will ultimately always be limited as civilian satellites are restricted to 0.5 m resolution. This means that mapping individual colonies will remain unfeasible, even if desired, despite high demand on computer processing power. In pelagic systems that are structured by large scale oceanographic patterns (Platt and Sathyendranath, 1999), such limitations may be less of an obstruction. Available spectral resolution can also restrict the usefulness of RS data for MPA management. It is for example difficult to discriminate between sand and coral skeleton without hyperspectral sensors (Klemas, 2011a; Purkis and Klemas, 2011; Wingfield et al., 2011). The availability of space-borne hyperspectral will increase in the future as more space-borne missions are planned (e.g., EnMap). Wide-spread use of hyperspectral images will however be limited by the skill and resources required to process such data.

For a realistic implementation of RS to support MPA management, financial and human resources need to be taken into account (see Appendix, Table 2A, for examples of prices for RS products). While excellent open source solutions exist for the processing and analysis of RS data (Knudby et al., 2011), commercial software solutions can be expected to continue dominating the education and training of the potential workforce. The limitations to reproducibility imposed by commercial software as currently debated (Ince et al., 2012; Morin et al., 2012) also apply to RS. While a lot of satellite data is now freely available, the very high resolution imagery still needs to be purchased. In addition, the comparatively large volumes of data might pose logistical and economic challenges for data transmission and storage (Strand et al., 2007).

## 6. Conclusion

RS can provide information on environmental parameters and habitats to improve the designation process of MPAs. Where additional (e.g., vessel- or air-borne) data collection is required to overcome limitations of space-borne RS data, it can provide initial information on which field sampling can be based. Monitoring after designation is then vital to ensure effectiveness and RS can provide important information to support such assessment, helping detect trends in habitat extent or other environmental variables relevant to biodiversity distribution. RS has great potential to feed indicator systems, e.g. the EBSAs and the recently proposed Essential Biodiversity Variables (Pereira et al., 2013) in a repeatable, objective and standardised way. As demonstrated throughout this review, RS can greatly contribute to help halt the loss of marine biodiversity and should be routinely taken into consideration for the implementation and monitoring of international agreements, such as the CBD 10% target. Better knowledge on the ecology of marine species will further increase the usefulness of RS for conservation. Future research will have to explore the constraints imposed by the depth limitation of optical RS, and identify species and conditions for which RS has the greatest potential. We also believe better communication between MPA managers and terrestrial practitioners could benefit the development of new RS applications.

## Appendix A.

See Tables 1A and 2A.

## References


Aburto-Oropeza, O., Erisman, B., Galland, G.R., Mascareñas-Osorio, I., Sala, E., Ezcurra, E., 2011. Large recovery of fish biomass in a no-take marine reserve. PLoS ONE 6, 1–7.

Arias-González, J.E., Acosta-González, G., Membrillo, N., Garza-Pérez, J.R., Castro-Pérez, J.M., 2011. Predicting spatially explicit coral reef fish abundance, richness and Shannon–Weaver index from habitat characteristics. Biodivers. Conserv. 21, 115–130.

Armenteras, D., Gast, F., Villareal, H., 2003. Andean forest fragmentation and the representativeness of protected natural areas in the eastern Andes, Colombia. Biol. Conserv. 113, 245–256.

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R.E., Jenkins, M., Jefferiss, P., Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S., Roughgarden, J., Trumper, K., Turner, R.K., 2002. Economic reasons for conserving wild nature. Science 297, 950–953.

Becker, J.J., Sandwell, D.T., Smith, W.H.F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S.-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G., Weatherall, P., 2009. Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. Mar. Geodesy 32, 355–371.

Bell, J.J., 2012. High connectivity between sea lough populations of a planktonic larval disperser with the adjacent open coast. Mar. Ecol. 33, 1–6.

Boersma, P.D., Parrish, J.K., 1999. Limiting abuse: marine protected areas, a limited solution. Ecol. Econ. 31, 287–304.

Bogazzi, E., Baldoni, A.N.A., Rivas, S., Martos, P., Reta, R.A.U.L., Orensanz, J.M.L., Lasta, M., Arciprete, D., Werner, F., 2005. Spatial correspondence between areas of concentration of Patagonian scallop (Zygochlamys patagonica) and frontal systems in the southwestern Atlantic. Fisheries Oceanogr., 359–376.

van Bommel, F.P.J., Heitkönig, I.M.A., Epema, G.F., Ringrose, S., Bonyongo, C., Veenendaal, E.M., 2005. Remotely sensed habitat indicators for predicting distribution of impala (*Aepyceros melampus*) in the Okavango Delta, Botswana. J. Trop. Ecol. 22, 101.

Bradford, R.W., Bruce, B.D., Chiswell, S.M., Booth, J.D., Jeffs, A., Wotherspoon, S., 2005. Vertical distribution and diurnal migration patterns of *Jasus edwardsii* phyllosomas off the east coast of the North Island, New Zealand. NZ J. Mar. Freshwater Res. 39, 593–602.

Brekke, C., Solberg, A.H.S., 2005. Oil spill detection by satellite remote sensing. Remote Sens. Environ. 95, 1–13.

Brey, T., Gerdes, D., 1997. Is Antarctic benthic biomass really higher than elsewhere? Antarct. Sci. 9, 266–267.

Brown, C.W., Connor, L.N., Lillibridge, J.L., Nalli, N.R., Legeckis, R.V., 2005. An introduction to satellite sensors, observations and techniques. In: Miller, R.L., Del Castillo, C.E., McKee, B.A. (Eds.), Remote Sensing of Coastal Aquatic Environments – Technologies, Techniques and Applications. Springer, Dordrecht, pp. 21–50.

Brusch, S., Lehner, S., Fritz, T., Soccorsi, M., Soloviev, A., Van Schie, B., 2011. Ship surveillance with TerraSAR-X. IEEE Trans. Geosci. Remote Sens. 49, 1092–1103.

Burrage, D.M., Heron, M.L., Hacker, J.M., Stieglitz, T.C., Steinberg, C.R., Prytz, A., 2002. Evolution and dynamics of tropical river plumes in the Great Barrier Reef: an integrated remote sensing and in situ study. J. Geophys. Res. 107, 1–17.

Campbell, J.B., Wynne, R.H., 2011. Introduction to Remote Sensing, 5th ed. The Guilford Press, New York City, United States.

CBD, 1992. Convention on Biological Diversity.

CBD, 2006. Framework for monitoring implementation of the achievement of the 2010 target and integration of targets into the thematic programmes of work. In: COP 8 Decision VIII/15.

CBD, 2010. Strategic plan for biodiversity 2011–2020. In: COP 10 Decision X/2.

Chape, S., Spalding, M., Jenkins, M.D., 2008. The World's Protected Areas, 1st ed. UNEP World Conservation Monitoring Center, Berkeley, United States.

Chiarolla, C., Kantai, T., Morgera, E., 2012. Summary of the fifth meeting of the Working Group on Marine Biodiversity Beyond Areas of National Jurisdiction , 7–11 May 2012.

Chollett, I., Mumby, P.J., Müller-Karger, F.E., Hu, C., 2012. Physical environments of the Caribbean Sea. Limnol. Oceanogr. 57, 1233–1244.

Corbane, C., Marre, F., Petit, M., 2008. Using SPOT-5 HRG data in panchromatic mode for operational detection of small ships in tropical area. Sensors 8 (5), 5837–5854, http://dx.doi.org/10.3390/s8052959.

Corbane, C., Najman, L., Pecoul, E., Demagistri, L., Petit, M., 2010. A complete processing chain for ship detection using optical satellite imagery. Int. J. Remote Sens. 31, 5837–5854.

Corliss, B.H., Brown, C.W., Sun, X., Showers, W.J., 2009. Deep-sea benthic diversity linked to seasonality of pelagic productivity. Deep Sea Research. Part I. Oceanographic Research Papers, vol. 56., pp. 835–841.

Cornforth, W., Fatoyinbo, T., Freemantle, T.P., Pettorelli, N., 2013. ALOS PALSAR to inform the conservation of mangroves: Sundarbans as a case study. Remote Sensing 5, 224–237.

Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R., Paruelo, V., Raskin, J., Sutton, R.G., Van den Belt, P.M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Cowen, R.K., Lwiza, K.M.M., Sponaugle, S., Paris, C.B., Olson, D.B., 2000. Connectivity of marine populations: open or closed? Science 287, 857–859.

D'Sa, E.J., Miller, R.L., 2005. Bio-optical properties of coastal waters. In: Miller, R.L., Del Castillo, C.E., McKee, B.A. (Eds.), Remote Sensing of Coastal Aquatic Environments – Technologies, Techniques and Applications. Springer, Dordrecht, pp. 129–155.

Dahdouh-Guebas, F., 2006. Mangrove forests and tsunami protection. In: 2006 McGraw Hill Yearbook of Science & Technology.

Dearden, P., Topelko, K., 2005. Establishing criteria for the identification of ecologically and biologically significant areas on the high seas. In: Background Paper Prepared for Fisheries and Oceans Canada. Marine Protected Areas Research Group, University of Victoria, Victoria, British Columbia, Canada, pp. 50.

DeFries, R., Hansen, A., Newton, A., Hansen, M.C., 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. Ecol. Appl. 15, 19–26.

Dekker, A., Brando, V., Anstee, J., Fyfe, S., 2006. Remote sensing of seagrass ecosystems: use of spaceborne and airborne sensors. In: Larkhum, A.W.D., Orth, R., Duarte, C.M. (Eds.), Seagrasses, Biology, Ecology and Conservation. Springer, Dordrecht, pp. 347–359.

Donato, T.F., Klemas, V.V., 2001. Remote sensing and modeling applications for coastal resource management. Geocarto Int. 16, 37–41.

Doran, P., Paul, D., Ripley, K., Risse, N., Van Alstine, J., Wagner, L., 2012. Summary of the United Nations Conference on Sustainable Development , 13–22 June 2012, Earth Negotiations Bulletin.

Doxaran, D., Froidefond, J., Lavender, S., Castaing, P., 2002. Spectral signature of highly turbid waters: application with SPOT data to quantify suspended particulate matter concentrations. Remote Sens. Environ. 81, 149–161.

Druel, E., Billé, R., Treyer, S., 2011. A legal scenario analysis for marine protected areas in areas beyond national jurisdiction. In: Report from the Boulogne-sur-Mer seminar, 19–21 September. IDDRI – IUCN – Agence des aires marines protégées, Paris, France.

Druon, J.-N., 2010. Habitat mapping of the Atlantic bluefin tuna derived from satellite data: Its potential as a tool for the sustainable management of pelagic fisheries. Mar. Policy 34, 293–297.

Duke, N.C., Pinzon, Z.S., Prada, M.C., 1997. Large-scale damage to mangrove forests following two large oil spills in Panama. Biotropica 29, 2–14.

Ardron, J., Ban, N., Bax, N., Bernal, P., Bograd, S., Corrigan, C., Dunstan, P., Game, E., Gjerde, K., Grantham, H., Halpin, P.N., Harrison, A.L., Hazen, E., Lagabrielle, E., Lascelles, B., Maxwell, S., McKenna, S., Nicol, S., Norse, E., Palacios, D., Reeve, L., Shillinger, G., Simard, F., Sink, K., Smith, F., Spadone, A., Würtz, M., 2011. Ecologically or biologically significant areas in the pelagic realm: examples & guidelines. In: Dunn, D.C. (Ed.), Workshop Report. IUCN, Gland, Switzerland, p. 44.

Elvidge, C., Dietz, J., Berkelmans, R., Andréfouët, S., Skirving, W., Strong, A., Tuttle, B., 2004. Satellite observation of Keppel Islands (Great Barrier Reef) 2002 coral bleaching using IKONOS data. Coral Reefs 23, 123–132.

FAO, 2012. The State of World Fisheries and Aquaculture. Rome, Italy.

Fenberg, P.B., Caselle, J.E., Claudet, J., Clemence, M., Gaines, S.D., Antonio García-Charton, J., Gonçalves, E.J., Grorud-Colvert, K., Guidetti, P., Jenkins, S.R., Jones, P.J.S., Lester, S.E., McAllen, R., Moland, E., Planes, S., Sørensen, T.K., 2012. The science of European marine reserves: status, efficacy, and future needs. Mar. Policy 36, 1012–1021.

Fraschetti, S., Terlizzi, A., Boero, F., 2008. How many habitats are there in the sea (and where)? J. Exp. Mar. Biol. Ecol. 366, 109–115.

Game, E.T., Grantham, H.S., Hobday, A.J., Pressey, R.L., Lombard, A.T., Beckley, L.E., Gjerde, K., Bustamante, R., Possingham, H.P., Richardson, A.J., 2009. Pelagic protected areas: the missing dimension in ocean conservation. Trends Ecol. Evol. 24, 360–369.

Godet, L., Fournier, J., Toupoint, N., Olivier, F., 2009. Mapping and monitoring intertidal benthic habitats: a review of techniques and a proposal for a new visual methodology for the European coasts. Prog. Phys. Geogr. 33, 378–402.

Greene, C.H., Baker, D.J., Miller, D.H., 2010. A very inconvenient truth. Oceanography 23, 214–218.

Gregr, E.J., Ahrens, A.L., Perry, R.I., 2012. Reconciling classifications of ecologically and biologically significant areas in the world's oceans. Mar. Policy 36, 716–726.

Gross, J.E., Goetz, S.J., Cihlar, J., 2009. Application of remote sensing to parks and protected area monitoring: introduction to the special issue. Remote Sens. Environ. 113, 1343–1345.

Hamel, M.A., Andréfouët, S., 2010. Using very high resolution remote sensing for the management of coral reef fisheries: review and perspectives. Mar. Pollut. Bull. 60, 1397–1405.

Hardman-Mountford, N.J., Hirata, T., Richardson, K.A., Aiken, J., 2008. An objective methodology for the classification of ecological pattern into biomes and provinces for the pelagic ocean. Remote Sens. Environ. 112, 3341–3352.

Hobday, A.J., Young, J.W., Moeseneder, C., Dambacher, J.M., 2011. Defining dynamic pelagic habitats in oceanic waters off eastern Australia. Deep Sea Research. Part II. Topical Studies in Oceanography, vol. 58., pp. 734–745.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. Science 318, 1737–1742.

Hörig, B., Kühn, F., Oschütz, F., Lehmann, F., 2001. Hymap hyperspectral remote-sensing to detect hydrocarbons. Int. J. Remote Sens. 22, 1413–1422.

Hughes, T.P., Bellwood, D.R., Folke, C.S., McCook, L.J., Pandolfi, J.M., 2007. No-take areas, herbivory and coral reef resilience. Trends Ecol. Evol. 22, 1–3.

Hyrenbach, K.D., Forney, K.A., Dayton, P.K., 2000. Marine protected areas and ocean basin management. Aquat. Conserv.: Mar. Freshwater Ecosyst. 458, 437–458.

Ince, D.C., Hatton, L., Graham-Cumming, J., 2012. The case for open computer programs. Nature 482, 485–488.

IPCC, 2011. Workshop Report of the Intergovernmental Panel on Cliamte Change Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems. IPCC Working Group II Technical Support Unit, Stanford, California, United States.

Irwin, A.J., Finkel, Z.V., 2008. Mining a sea of data: deducing the environmental controls of ocean chlorophyll. PLoS ONE 3 (11), e3836, http://dx.doi.org/10.1371/journal.pone.0003836.

Kelleher, 1999. Guidelines for Marine Protected Areas, WCPA Best. IUCN Publication, Gland.

Kirkman, H., 1996. Baseline and monitoring methods for seagrass meadows. J. Environ. Manage., 191–201.

Klemas, V., 2010. Tracking oil slicks and predicting their trajectories using remote sensors and models: case studies of the sea princess and deepwater horizon oil spills. J. Coastal Res. 265, 789–797.

Klemas, V., 2011a. Remote sensing techniques for studying coastal ecosystems: an overview. J. Coastal Res. 27, 2–17.

Klemas, V., 2011b. Beach profiling and LIDAR bathymetry: an overview with case studies. J. Coastal Res. 277, 1019–1028.

Klemas, V., 2012. Fisheries Applications of Remote Sensing: An Overview. Fisheries Research.

Knudby, A., Roelfsema, C., Lyons, M., Phinn, S., Jupiter, S., 2011. Mapping fish community variables by integrating field and satellite data, object-based image analysis and modeling in a traditional Fijian Fisheries Management Area. Remote Sens. 3, 460–483.

Koldewey, H.J., Curnick, D., Harding, S., Harrison, L.R., Gollock, M., 2010. Potential benefits to fisheries and biodiversity of the Chagos Archipelago/British Indian Ocean Territory as a no-take marine reserve. Mar. Pollut. Bull. 60, 1906–1915.

Kuchler, D., Jupp, D., Claasen, D., Bour, W., 1986. Coral reef remote sensing applications. Geocarto Int. 4, 3–15.

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T.V., Dech, S., 2011. Remote sensing of mangrove ecosystems: a review. Remote Sens. 3, 878–928.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J.-M., Hare, S.R., Ottersen, G., Perry, R.I., Roy, C., Van der Lingen, C.D., Werner, F., 2006. Climate variability, fish, and fisheries. J. Climate 19, 5009–5030.

Lengyel, S., Kobler, A., Kutnar, L., Framstad, E., Henry, P.-Y., Babij, V., Gruber, B., Schmeller, D., Henle, K., 2008. A review and a framework for the integration of biodiversity monitoring at the habitat level. Biodivers. Conserv. 17, 3341–3356.

Marine Reserves Coalition, 2012. The race to protect our oceans – MRC delivers MPA league table at Rio + 20 [WWW Document]. Marine Protected Area (MPA) League Table of Nations. http://www.marinereservescoalition.org/2012/06/18/the-race-to-protect-our-oceans-mrc-delivers-mpa-league-table-at-rio-20/

Maynard, J.a., Turner, P.J., Anthony, K.R.N., Baird, A.H., Berkelmans, R., Eakin, C.M., Johnson, J., Marshall, P.a., Packer, G.R., Rea, A., Willis, B.L., 2008. ReefTemp: an interactive monitoring system for coral bleaching using high-resolution SST and improved stress predictors. Geophysical Research Letters 35, 1–5.

McCauley, D.J., Micheli, F., Young, H.S., Tittensor, D.P., Brumbaugh, D.R., Madin, E.M.P., Holmes, K.E., Smith, J.E., Lotze, H.K., DeSalles, P.A., Arnold, S.N., Worm, B., 2010. Acute effects of removing large fish from a near-pristine coral reef. Mar. Biol. 157, 2739–2750.

Mellin, C., Andréfouët, S., Kulbicki, M., 2009. Remote sensing and fish–habitat relationships in coral reef ecosystems: Review and pathways for multi-scale hierarchical research. Mar. Pollut. Bull. 58, 11–19.

Mellin, C., Parrott, L., Andréfouët, S., Bradshaw, C.J.A., MacNeil, M.A., Caley, M.J., 2012. Multi-scale marine biodiversity patterns inferred efficiently from habitat image processing. Ecol. Appl. 22, 792–803.

Miller, R.L., Del Castillo, C.E., McKee, B.A. (Eds.), 2005. Remote Sensing of Coastal Aquatic Environments. , 1st ed. Springer, Dordrecht, The Netherlands.

Mora, C., Costello, M., 2006. Coral reefs and the global network of marine protected areas. Science 312, 1750–1751.

Morin, A., Urban, J., Adams, P.D., Foster, I., Sali, A., Baker, D., Sliz, P., 2012. Shining light into black boxes. Science 336, 159–160.

Muller-Karger, F.E., Hu, C., Andréfouet, S., Varela, R., Thunell, R., 2005. The color of the coastal ocean. In: Miller, R.L., Del Castillo, C.E., McKee, B.A. (Eds.), Remote Sensing of Coastal Aquatic Environments - Technologies, Techniques and Applications. Springer, Dordrecht, pp. 101–127.

Mumby, P., Green, E., Edwards, A., Clark, C., 1997. Coral reef habitat mapping: how much detail can remote sensing provide? Mar. Biol. 130, 193–202.

Mumby, P.J., Skirving, W., Strong, A.E., Hardy, J.T., LeDrew, E.F., Hochberg, E.J., Stumpf, R.P., David, L.T., 2004. Remote sensing of coral reefs and their physical environment. Mar. Pollut. Bull. 48, 219–228.

Nagelkerken, I., Blaber, S.J.M., Bouillon, S., Green, P., Haywood, M., Kirton, L.G., Meynecke, J.O., Pawlik, J., Penrose, H.M., Sasekumar, A., Somerfield, P.J., 2008. The habitat function of mangroves for terrestrial and marine fauna: a review. Aquat. Bot. 89, 155–185.

O'Leary, B.C., Brown, R.L., Johnson, D.E., Von Nordheim, H., Ardron, J., Packeiser, T., Roberts, C.M., 2012. The first network of marine protected areas (MPAs) in the high seas: the process, the challenges and where next. Mar. Policy 36, 598–605.

Oney, B., Shapiro, A., Wegmann, M., 2011. Evolution of water quality around the Island of Borneo during the last 8-years. Procedia Environ. Sci. 7, 200–205.

Ottaviani, M., Cairns, B., Chowdhary, J., Van Diedenhoven, B., Knobelspiesse, K., Hostetler, C., Ferrare, R., Burton, S., Hair, J., Obland, M.D., Rogers, R., 2012. Polarimetric retrievals of surface and cirrus clouds properties in the region affected by the Deepwater Horizon oil spill. Remote Sens. Environ. 121, 389–403.

Palacios, D.M., Bograd, S.J., Foley, D.G., Schwing, F.B., 2006. Oceanographic Characteristics of Biological Hot Spots in the North Pacific: A Remote Sensing Perspective. Deep Sea Research Part II: Topical Studies in Oceanography., pp. 250–269.

Pereira, H., Ferrier, S., Walters, M., 2013. Essential biodiversity variables. Science 339, 277–278.

Petersen, S.L., Phillips, R.A., Ryan, P.G., Underhill, L.G., 2008. Albatross overlap with fisheries in the Benguela upwelling system: implications for conservation and management. Endang. Species Res. 5, 117–127.

Pettorelli, N., Chauvenet, A.L.M., Duffy, J.P., Cornforth, W., Meillere, A.A., Baillie, J.E.M., 2012. Tracking the effect of climate change on ecosystem functioning using protected areas: Africa as a case study. Ecol. Indic. 20, 269–276.

Pettorelli, N., Katzner, T., Gordon, I., Garner, T., Mock, K., Redpath, S., Gompper, M., 2009. Possible consequences of the Copenhagen climate change meeting for conservation of animals. Anim. Conserv. 12, 503–504.

Pfeifer, M., Disney, M., Quaife, T., Marchant, R., 2011. Terrestrial ecosystems from space: a review of earth observation products for macroecology applications. Global Ecol. Biogeogr. 21, 603–624.

Phinn, S.R., Roelfsema, C.M., Mumby, P.J., 2012. Multi-scale, object-based image analysis for mapping geomorphic and ecological zones on coral reefs. Int. J. Remote Sen. 33, 3768–3797.

Platt, T., Sathyendranath, S., 1999. Spatial structure of pelagic ecosystem processes in the global ocean. Ecosystems 2, 384–394.

Purkis, S., Riegl, B.M., 2005. Spatial and temporal dynamics of Arabian Gulf coral assemblages quantified from remote-sensing and in situ monitoring data. Mar. Ecol. Prog. Ser. 287, 99–113.

Purkis, S.J., Klemas, V., 2011. Remote Sensing and Global Environmental Change, 1st ed. Blackwell Publishing Inc., West Sussex, UK.

Qiu, F., Fang, W., Fang, G., 2011. Seasonal-to-interannual variability of chlorophyll in central western South China Sea extracted from SeaWiFS. Chin. J. Ocean. Limnol. 29, 18–25.

Queiroz, N., Humphries, N.E., Noble, L.R., Santos, A.M., Sims, D.W., 2012. Spatial dynamics and expanded vertical niche of blue sharks in oceanographic fronts reveal habitat targets for conservation. PLoS ONE 7, e32374.

Rabaut, M., Degraer, S., Schrijvers, J., Derous, S., Bogaert, D., Maes, F., Vincx, M., Cliquet, A., 2009. Policy analysis of the MPA process in temperate continental shelf areas. Aquat. Conserv.: Mar. Freshwater Ecosyst. 608, 596–608.

Risien, C.M., Chelton, D.B., 2008. A global climatology of surface wind and wind stress fields from eight years of QuikSCAT scatterometer data. J. Phys. Oceanogr. 38, 2379–2413.

Roberts, C.M., 2000. Selecting marine reserve locations: optimality versus opportunism. Bull. Mar. Sci. 66, 581–592.

Roberts, C.M., 2005. Marine protected areas and biodiversity. In: Norse, E.A., Crowder, L.B. (Eds.), Marine Conservation Biology – The Science of Maintaing the Sea's Biodiversity. Island Press, Washington, DC, United States.

Rohmann, S.O., Monaco, M.E., 2005. Mapping Southern Florida's Shallow-water Coral Ecosystems: An Implementation Plan (No. 19). Silver Spring, MD.

Rowlands, G., Purkis, S., Riegl, B., Metsamaa, L., Bruckner, A., Renaud, P., 2012. Satellite imaging coral reef resilience at regional scale. A case-study from Saudi Arabia. Mar. Pollut. Bull. 64, 1222–1237.

Rowlands, G.P., Purkis, S.J., Riegl, B.M., 2008. The 2005 coral-bleaching event Roatan (Honduras): use of pseudo-invariant features (PIFs) in satellite assessments. J. Spatial Sci. 53, 99–112.

Royer, T.C., Vermersch, J.A., Weingartner, T.J., Niebauer, H.J., Muench, R.D., 1990. Ocean circulation influencing the Exxon Valdez oil spill. Oceanography 3, 3–10.

CFS Sala III, O.E., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Salm, R.V., Price, A., 1995. Selection of marine protected areas. In: Gubbay, S. (Ed.), Marine Protected Areas: Principles and Techniques for Management. Springer, London, United Kingdom, pp. 15–31.
Sandin, S.A., Smith, J.E., Demartini, E.E., Dinsdale, E.A., Donner, S.D., Friedlander, A.M., Konotchick, T., Malay, M., Maragos, J.E., Obura, D., Pantos, O., Paulay, G., Richie, M., Rohwer, F., Schroeder, R.E., Walsh, S., Jackson, J.B.C., Knowlton, N., Sala, E., 2008. Baselines and degradation of coral reefs in the Northern Line Islands. PLoS ONE 3, e1548.
Scopélitis, J., Andréfouët, S., Phinn, S., Arroyo, L., Dalleau, M., Cros, A., Chabanet, P., 2010. The next step in shallow coral reef monitoring: combining remote sensing and in situ approaches. Mar. Pollut. Bull. 60, 1956–1968.
Selig, E.R., Casey, K.S., Bruno, J.F., 2012. Temperature-driven coral decline: the role of marine protected areas. Global Change Biol. 18, 1561–1570.
Sequeira, A., Mellin, C., Rowat, D., Meekan, M.G., Bradshaw, C.J.A., 2012. Ocean-scale prediction of whale shark distribution. Divers. Distrib. 18, 504–518.
Sheppard, C., Rayner, N.A., 2002. Utility of the Hadley Centre sea ice and sea surface temperature data set (HadISST1) in two widely contrasting coral reef areas. Mar. Pollut. Bull. 44, 303–308.
Sheppard, C.R.C., Ateweberhan, M., Bowen, B.W., Carr, P., Chen, C., Clubbe, a., Craig, C., Ebinghaus, M.T., Eble, R., Fitzsimmons, J., Gaither, N., Gan, M.R., Gollock, C.-H., Guzman, M., Graham, N., Harris, N.A.J., Jones, A., Keshavmurthy, R., Koldewey, S., Lundin, H., Mortimer, C.G., Obura, J.A., Pfeiffer, D., Price, M., Purkis, a.R.G., Raines, S., Readman, P., Riegl, J.W., Rogers, B., Schleyer, A., Seaward, M., Sheppard, M.R.D.a., Tamelander, L.S., Turner, J., Visram, J.R., Vogler, S., Vogt, C., Wolschke, S., Yang, H., Yang, J.M.-C., Yesson, S.-Y.C., 2012. Reefs and islands of the Chagos Archipelago, Indian Ocean: why it is the world's largest no-take marine protected area. Aquat. Conserv. Mar. Freshwater Ecosyst. 22, 232–261.
Short, F., Carruthers, T., Dennison, W., Waycott, M., 2007. Global seagrass distribution and diversity: a bioregional model. J. Exp. Mar. Biol. Ecol. 350, 3–20.
Smith, W.H., 1997. Global sea floor topography from satellite altimetry and ship depth soundings. Science 277, 1956–1962.
Stevens, T., 2002. Rigor and representativeness in marine protected area design. Coast. Manage. 30, 237–248.
Strand, H., Hoft, R., Strittholt, J., Horning, N., Miles, L., Fosnight, E., Turner, W., 2007. Sourcebook on remote sensing and biodiversity indicators. In: CBD Technical Series. Secretariat of the Convention on Biological Diversity, Gland, Switzerland, pp. 103.
Tittensor, D.P., Mora, C., Jetz, W., Lotze, H.K., Ricard, D., Berghe, E., Vanden Worm, B., 2010. Global patterns and predictors of marine biodiversity across taxa. Nature 466, 1098–1101.
Townsend, P.A., Lookingbill, T.R., Kingdon, C.C., Gardner, R.H., 2009. Spatial pattern analysis for monitoring protected areas. Remote Sens. Environ. 113, 1410–1420.
Valavanis, V.D., Pierce, G.J., Zuur, A.F., Palialexis, A., Saveliev, A., Katara, I., Wang, J., 2008. Modelling of essential fish habitat based on remote sensing, spatial analysis and GIS. Hydrobiologia 612, 5–20.
Valdes, L., Peterson, W., Church, J., Brander, K., Marcos, M., 2009. Our changing oceans: conclusions of the first international symposium on the effects of climate change on the world's oceans. ICES J. Mar. Sci. 66, 1435–1438.
Vermeij, M.J.A., Marhaver, K.L., Huijbers, C.M., Nagelkerken, I., Simpson, S.D., 2010. Coral larvae move toward reef sounds. PLoS ONE 5, 4.
Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395.
Weng, Q. (Ed.), 2010. Remote Sensing of Coastal Environments. , 1st ed. Taylor and Francis Ltd., Boca Raton, Florida, USA.
Williams, R., Gero, S., Bejder, L., Calambokidis, J., Kraus, S.D., Lusseau, D., Read, A.J., Robbins, J., 2011. Underestimating the damage: interpreting cetacean carcass recoveries in the context of the Deepwater Horizon/BP incident. Conserv. Lett. 4, 228–233.
Wilson, S.K., Dolman, A.M., Cheal, A.J., Emslie, M.J., Pratchett, M.S., Sweatman, H.P.A., 2009. Maintenance of fish diversity on disturbed coral reefs. Coral Reefs 28, 3–14.
Wingfield, D.K., Peckham, S.H., Foley, D.G., Palacios, D.M., Lavaniegos, B.E., Durazo, R., Nichols, W.J., Croll, D.A., Bograd, S.J., 2011. The making of a productivity hotspot in the coastal ocean. PLoS ONE 6, e27874.
Worm, B., Hilborn, R., Baum, J.K., Branch, T.a, Collie, J.S., Costello, C., Fogarty, M.J., Fulton, E.a, Hutchings, J.a, Jennings, S., Jensen, O.P., Lotze, H.K., Mace, P.M., McClanahan, T.R., Minto, C., Palumbi, S.R., Parma, A.M., Ricard, D., Rosenberg, A.a, Watson, R., Zeller, D., 2009. Rebuilding global fisheries. Science 325, 578–585.
Yamano, H., Tamura, M., 2004. Detection limits of coral reef bleaching by satellite remote sensing: simulation and data analysis. Remote Sens. Environ. 90, 86–103.

## Glossary

*Remote sensing:* the derivation of information by analysing electromagnetic radiation that is reflected by the earth's surface and received by a sensor
*Sensor:* an instrument capable of recording electromagnetic radiation
*Active sensors:* sensors that emit radiation and make use of the reflected signal. Examples of active sensors include Radar and LIDAR.
*Passive sensors:* sensors that rely on natural radiation sources (e.g. sun light) to be reflected
*Band:* width of wavelengths within which sensors records the intensity of electromagnetic radiation. A sensor usually records several bands.
*Spectral resolution:* the width and number of bands that a sensor records, i.e. how well different wavelengths can be differentiated.
*Spatial resolution:* the size of one pixel in a remote sensing product.
*Temporal resolution:* refers to the revisit time or repeat viewing frequency; i.e. the time how long it takes until the sensor passes over the same area again.
*Swath:* the area in which a sensor can record during a by-pass.