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LAGOONS AND COASTAL WETLANDS

Defining the coast and sentinel ecosystems for coastal observations of global change

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Abstract The detection, attribution and prediction of global and large scale regional change are goals for the Global Observing Systems of the United Nations. Coastal areas are particularly sensitive to global change, but there is a variety of limitations to universal coverage of observations. The coastal module of the Global Terrestrial Observing System (C-GTOS) considers sentinel ecosystems to address these goals for the terrestrial, wetland and freshwater ecosystems of the coast. Sentinel ecosystems for observing systems are a limited number of well understood systems that have substantial datasets and are observed in a sustained fashion, forming an early warning and core system for broader regional and global change. A necessary step in the development of C-GTOS is the examination of current definitions of coastal areas by anticipated users and information providers, and identification of potential coastal networks and sites. We applied the sentinel system framework to the selection of C-GTOS observation sites from several international programs using various global delineations of coastal areas. Delineations were based on the most common definitions of the coast adopted by potential C-GTOS users and information providers, and included mapped areas of various distance from the coastline, coastal areas of low elevation, and a seaward boundary matching the Economic Exclusive Zone (EEZ). Decreases in the number of sites within each international program occurred with each definition marking area closer to the coastline. The Ramsar Convention on Wetlands demonstrates the greatest percentage of coastal sites by any definition. The process of choosing specific sentinel sites for C-GTOS continues from this initial screening, and is the next step towards the development of an in situ site network supporting the observation of global and large scale change.

Keywords Coast · Global Terrestrial Observing System · ecosystems · Long-term monitoring · Ramsar Convention on Wetlands · World Heritage Convention

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Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues

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Introduction

The detection, attribution and prediction of global and large scale regional change have become goals for numerous national and multinational organizations. The United Nations contributes to these goals through its Global Observing Systems. The observing systems are divided into three major programs: Global Terrestrial Observing System (GTOS), Global Ocean Observing System (GOOS), and Global Climate Observing System (GCOS). The coast is one area where global change appears critically important and where interaction among the observing systems is essential for effectively meeting their goals. Both GOOS and GTOS are developing coordinated coastal programs and contributing to the Integrated Global Observing Strategy (IGOS), the observing system strategy fostering cooperation among various UN and national partners, including space agencies.

While coordination occurs, the two coastal programs have taken somewhat different approaches. The coastal module of GOOS is developing an extensive system linking regional and national programs and has focused on establishing a core observation system and promoting the activities of the individual, generally national, programs (UNESCO, 2003b). The coastal module of GTOS (C-GTOS) has focused on a more limited group of specific issues than GOOS and has separated its implementation into two phases (FAO, 2005). The first phase addresses a set of defined priority proposals. These are designed to provide tests of concept for the observing system and initial important products that can be built upon for the second phase. The second phase is the mature system that complements the coastal module of GOOS, and other coastal observing initiatives, and develops the four phenomena of interest that are the long-term focus issues of C-GTOS identified in the *C-GTOS Strategic Design and Phase 1 Implementation Plan* (FAO, 2005):

- Human dimensions, land use, land cover and critical habitat alteration.
- Sediment loss and delivery.
- Water cycle and water quality.
- Effects of sea level change, storms and flooding.

One of the major challenges in establishing and maintaining a global network for observations of global change is ensuring adequate spatial and temporal extent of the observations. In this article, we describe initial steps toward the development of a global coastal observing system by reviewing (1) the general concerns of observing systems and more specifically coastal in situ observations, (2) the definition and delineation of the coast by potential users, and (3) the application of a sentinel system framework as a means to identify and establishing a network to meet observing system goals. This work stems from one of the phase 1 priority products of the C-GTOS plan ''Management of conservation and cultural sites in the coastal zone'' (FAO, 2005).

Need for in situ networks and issues in monitoring

Worldwide coverage of observations is key to global observing systems, but for many variables, if not most, such coverage is beyond our current capabilities. Global coverage may exist for satellite and other remote imagery, but the number of variables measured is limited. Not all countries are capable of making sustained, operational, and accessible observations with political, social and economic factors sometimes preventing conducive conditions for these capabilities. The limitations of in situ measurements are particularly apparent; as not all variables can be remotely sensed, and those that can still require some form of in situ validation. Total in situ coverage is lacking no matter what political, social and economic conditions. Even in developed countries the institutional mechanisms for coordinated reporting on in situ monitoring data are far less advanced than those of remote sensing efforts. All things cannot be measured at all places, therefore interpolation is always needed, but the frequency and consistency of measurements is often a limiting factor. Finally, uncertainties of the observations, the derived information, and resultant models are difficult to assess.

International observing systems initiatives, such as GTOS, GOOS, GCOS, IGOS, and the Global Earth Observation System of Systems (GEOSS), provide means to coordinate observing system efforts among countries, assist in implementation and training, and identify gaps for prioritized development and funding. GEOSS is an intergovernmental network that plans to improve observing system significantly over the next 10 years, supported by the efforts the four proceeding initiatives. The observing systems themselves cannot directly make the necessary measurements. Instead, the objectives of these programs will only be achieved through countries contributing observations from their existing or proposed program activities and thus funding. In turn, the observing systems and international donor community must facilitate new measurements where these are lacking, and play an essential role in the coordination, analysis and communication of regional and global information.

The sentinel system concept and its application to global and regional observations

How then can observations be made efficaciously? A long-term goal of observing systems is to build capacity for all nations to make and report observations, but this requires significant commitment and time. The ability to reach the necessary capacity for all nations will be measured in decades at best, so more near-term strategies must be taken. Two such strategies, which are not mutually exclusive, are to (1) develop models that interpolate and extrapolate to areas with little to no data, and (2) observe and build upon ''sentinel ecosystems'', forming an early warning and core system for broader regional and global change. Sentinel Ecosystems refer to a limited number of well understood systems that have substantial datasets and are observed in a sustained fashion. Jassby (1998) previously defined sentinel ecosystems in another context and considered the implications of the concept with three aquatic ecosystems. The framework for his site selection was based on the following criteria:

- ''... relatively small number of locations are chosen for intensive study, each location being selected to represent a certain, preferably large, class of ecosystems.''
- ''some subset ... must encounter the stressor,''
- ''some [sites] ... must have the critical features that cause responsiveness to that stressor,''
- ''background variability ... must not disguise the response to the stressor of interest.''

With some modification, Jassby's sentinel system framework has application for observing systems of global or regional change, although this was not its original purpose. Furthermore, the sentinel system concept has many advantages in the short- and long-term development of observing systems; it is complementary to the site selection methodologies and policy frameworks of existing programs that the coastal observing system will draw upon, and addresses issues of scale and hierarchy of processes to be observed.

A sentinel ecosystem framework for global observing systems may have several features added to those identified by Jassby, advantageous to the assessment of global and regional change:

- These ecosystems may be both natural and human influenced.
- Where possible, they should meet the criteria outlined in Jassby's approach (both representative of classes of ecosystem and responsiveness to stressors). Although, different approaches will be required regionally, with greater flexibility in the application of criteria for sites in countries with limited resources.
- These systems will likely be important enough for society to support long-term study. Systems important to human society often have historic records and commitment to ongoing study—both for research and monitoring.
- Their value may be for conservation, natural heritage, cultural and socio-economic purposes, providing a diversity of potential assessment capabilities.
- Lastly, these sites are likely to be already part of at least one international network of sites, providing mechanisms for information access.

There are several advantages to this expanded strategy that contribute to the development and

management of observing systems, as well as the individual sites themselves. Firstly, the sentinel ecosystems are directly useful for long-term observations of the particular location and representative for assessment of a broader group of ecosystems. Secondly, the work builds capacity for providing sustained and quality-assured information for the development, validation, and evaluation of large scale modeling and comparative change studies (Rastetter et al., 2003). Once the capacity is established, it can be extended; models can be transferred with greater confidence to other locations and adapted for use in regional and global studies (Seitzinger & Kroeze, 1998; Alexander et al., 2002; Seitzinger et al., 2002; Rastetter et al., 2003). Thirdly, this also builds sound region-specific understanding of coastal systems to support regionalized modeling efforts, advocated in advanced global coastal change programs (Church, 2001). Finally, this approach bolsters existing networks of monitoring sites and their activities; it links networks with vested interests in sustained monitoring, and supports current global and regional program activities for monitoring and conservation of heritage areas. These are all necessary steps for global change assessment.

We consider sentinel sites as ecosystems and use the terms somewhat interchangeably. This recognizes a broad definition of ecosystems (Christian, 2003a) that includes the hierarchical nature of observing systems and their components. Sentinel ecosystem observations provide various links to global assessment. Hallmarks of ecosystem studies are elemental cycling and trophic dynamics, both important to global change. In observing ecosystems, often other hierarchical levels of interest are considered (Allen & Hoekstra, 1992; Christian, 2003a). Community structure and population dynamics of keystone and ''flagship'' species may be assessed in the broader, ecosystem-level context. In turn, a context for ecosystem dynamics and structure is the landscape, perhaps watershed, condition. Global assessment is at least partially derived from some metric (e.g., sum, mean, median) of the conditions of the populations of individual locations around the world. The sentinel ecosystems represent important, first-order sites to sample from these populations.

Definition and delineation of coastal areas for a coastal observing system

Defining the coastal system is an early and obvious task for such efforts as the development of a GTOS coastal observing module. C-GTOS (FAO, 2005) reviewed the definitions and approaches adopted by both potential users and collaborators dealing with coastal issues, grouping these as either multilateral environmental agreements and initiatives, international organizations, and global/regional/national assessments (FAO, 2005). A range of definitions of coastal areas and ecosystems were obtained, showing increasing complexity over time (Table 1). Earlier definitions focused on geographic boundaries and management units (e.g., Exclusive Economic Zone [EEZ] and various Integrated Coastal Area Management [ICAM] guidelines). More recent coastal management initiatives have had a greater focus on ecosystem functionality and include interaction with human use dynamics. The ecosystem approach as endorsed by the Convention on Biological Diversity (CBD), the Millennium Ecosystem Assessment (MA), and other current global assessments and initiatives are consistent with this (Millennium Assessment, 2003). These approaches are not mutually exclusive. Accordingly, C-GTOS has not adopted a definition of the coastal zone in a single way, but will use an adaptive approach specific to the user needs of products to be developed.

In the application of the sentinel site framework for developing a coastal observing system, multiple definitions of the coast are desirable, encompassing as many existing program ''coastal'' sites, ecosystem types, management zones, and monitoring activities as possible (Table 1). The four focus issues of C-GTOS mentioned earlier will be evaluated within different geographic delineations. For example, ''Human dimensions, land use, land cover and critical habitat alteration'' might be considered over a larger area than ''Effects of sea level change, storms and flooding''. Furthermore, the selection

Table 1 Definitions of coastal areas and ecosystems used by international initiatives with coastal mandates (direct quotes are shown in italics)

International initiatives with coastal mandates	Definitions of coastal areas or associated ecosystems and habitats
Multilateral environmental agreements and initiatives	
The United Nations Millennium Assessment (MA) is an international work program designed to meet scientific information needs concerning the consequences of ecosystem change and available options for response. Documentation: Millennium Assessment (2003); http://www.millenniumassessment.org/.	The Millennium Assessment reports on ecosystems and ecosystems services within six reporting categories including the coastal zone. Each category is defined by (i) a central concept and (ii) boundary limits for mapping. *Central Concept: interface between ocean and land, extending seawards to about the middle of the continental shelf and inland to include all areas strongly influenced by the proximity to the ocean. Boundary Limits for Mapping: area between 50 m below mean sea level and 50 m above the high tide level or extending landward to a distance 100 km from shore. Includes coral reefs, intertidal zones, estuaries, coastal aquaculture and sea grass communities.* MA reporting categories are not mutually exclusive: *a wetland ecosystem in a coastal region may be examined both in the MA analysis of coastal systems as well as in its analysis of inland water systems.* Differentiation is made between the coastal zone and other adjacent reporting categories based on the definition of boundary limits for mapping. For example, the coastal zone has a shared boundary with bordering marine systems (*>50 m depth*). Permanent inland waters of inland water systems are also separated spatially from respective coastal systems (*permanent water bodies inland from the coastal zone*).
The Ramsar Convention on Wetlands held in Ramsar, Iran, in 1971, covers all aspects of wetland conservation, recognizing wetlands' importance for biodiversity conservation and the well-being of human communities. Documentation: Ramsar Convention on Wetlands (1971) and associated key documents (Articles 1.2 and 2.1); http://www.ramsar.org/.	The Ramsar definition of wetlands accounts for a wide variety of coastal habitats. The Ramsar Classification System for Wetland Type lists the following types of coastal wetlands: permanent shallow marine waters; marine subtidal aquatic beds; coral reefs; rocky marine shores; sand, shingle or pebble shores; estuarine waters; intertidal mud, sand or salt flats; intertidal marshes; intertidal forested wetlands; coastal brackish/saline lagoons; coastal freshwater lagoons, and karst and other subterranean hydrological systems. The Convention on Wetlands describes wetlands as: *areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters.* [Wetlands] *may incorporate adjacent riparian and coastal zones, islands or bodies of marine water deeper than six meters at low tide lying within the wetland.*
Agenda 21 was adopted at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil (1992). It is a key integrated coastal area management document and led the way for subsequent coastal area agreements and legal instruments. Documentation: UNCED (1992); http://www.un.org/esa/sustdev/.	Chapter 17 includes seven major program areas that relate to coastal areas and management with some definition of the coast. The first *integrated management and sustainable development of coastal areas, includes the area covered by Exclusive Economic Zones.*

Table 1 continued

International initiatives with coastal mandates	Definitions of coastal areas or associated ecosystems and habitats
International organizations	
The United Nations Environment Programme (UNEP) is developing a the Assessment of the Coastal and Marine Environment (CME) as a contribution to the planned Global Marine Assessment (GMA). This expands upon existing assessment initiatives coastal and marine ecosystems. Multiple other coastal-related initiatives have been conducted, such as the program on Integrated Coastal Area and River Basin Management (ICARM) relevant to the terrestrial coast. Documentation: UNEP (2004); UNEP/MAP/PAP (1999); http://www.unep-wcmc.org/marine/.	An exact definition and spatial extent is not specified for coastal habitats that are part of the CME assessment. Instead an adaptable approach is proposed to determine the scope, based on existing assessment methodologies: *the geographical structure of the assessment has to be flexible and based on natural, political and institutional realities. Existing geographical and programmatic structure ...should be used where appropriate.* The large variety of habitats in coastal waters is noted, including *coastal wetlands, estuaries and deltas, mangrove, coastal reef and seagrass beds.* ICARM guidelines identify the area of concern as encompassing *the catchment, the coastal zone and the near-shore coastal waters...Four interacting zones are taken into consideration: coastal waters, the coastal strip, estuary, and the coastal plain.*
The United Nations Education Scientific and Cultural Organization (UNESCO) has numerous coastal initiatives relating to coastal assessments taking place primarily through the Intergovernmental Oceanographic Commission (IOC), which (as with many UN coastal initiatives) collaborates routinely with Small Island Developing States (SIDS). Integrated Coastal Area Management (ICAM) is one such program, which is currently developing indicators for assessment of the coastal area. Documentation: UNESCO (2003a); http://www.ioc.unesco.org/.	A guide published on the use of indicators for ICAM states that catchment management deals with land usages in the coastal stream and river runoff areas for lagoons, bays and estuaries.
The Food and Agriculture Organization (FAO) of the United Nations has multiple initiatives addressing coastal areas, their management and the production of relevant guidelines, such as the Code of Conduct for Responsible Fisheries. Documentation: Scialabba (1998); FAO (1995); http://www.fao.org/.	The FAO ICAM guidelines state: *an ICM program embraces all of the coastal and upland areas, the uses of which can affect coastal waters and the resources therein, and extends seaward to include that part of the coastal ocean that can affect the land of the coastal zone. The ICM program may also include the entire ocean area under national jurisdiction (Exclusive Economic Zone), over which national governments have stewardship responsibilities under both the Law of the Sea Convention and UNCED.*
Global/national assessment initiatives	
The Coastal Ocean Observations Module of the Global Ocean Observing System (C-GOOS) has been developed with the goal of monitoring, assessing, and predicting the effects of natural variations and human activities on the marine environment and ecosystems of the coastal ocean. Documentation: UNESCO (2003b); http://www.ioc.unesco.org/goos/coop.htm.	Coastal, as defined for use in the Coastal Module of GOOS, refers to *regional mosaics of habitats including intertidal habitats (mangroves, marshes, mud flats, rocky shores, sandy beaches), semi-enclosed bodies of water (estuaries, sounds, bays, fjords, gulfs, seas), benthic habitats (coral reefs, sea grass beds, kelp forests, hard and soft bottoms) and the open waters of the coastal ocean to the seaward limits of the Exclusive Economic Zone (EEZ)*, i.e. from the head of the tidal waters to the outer limits of the EEZ. The definition of coastal zone is adopted from Nicholls and Small (2002): *the land margin within 100 km of the coastline or less than 100 m above mean low tide, which ever comes first.*

Table 1 continued

International initiatives with coastal mandates	Definitions of coastal areas or associated ecosystems and habitats
The International Geosphere-Biosphere Project's (IGBP) mission is to deliver scientific knowledge to help human societies develop in harmony with earth's environment. The mandate of Land-Ocean Interactions in the Coastal Zone (LOICZ), as a core project of IGBP, is to address global change in coastal systems and to inform earth system sciences on the relevance of global change in coastal systems. Documentation: IGBP Secretariat (2004); http://www.loicz.org/.	LOICZ includes in its statement of major goals the following reference to the costal zone and scales of activity: *to provide a framework...and to act as a means to focus on key issues concerning human activity and resource use in the coastal zone by applying the full water-continuum scale including the river catchments and the EEZ as spatial scales of major human interventions.*
The Global International Waters Assessment (GIWA) assesses international waters and associated basins, providing needed information for related Global Environment Facility (GEF) activities. A GEF objective for this focus area is to serve primarily as a catalyst to the development of a more comprehensive, ecosystem-based approach to managing international waters and their drainage basins. Documentation: Pernetta and Mee (1998); UNEP (1999); http://www.giwa.net/; http://www.gefweb.org/.	International waters and their drainage basins, which include coastal areas, are one of four priority areas identified by GEF and assessed by GIWA. These combined areas include different coastal habitats *comprising marine, coastal and freshwater areas, and surface waters as well as groundwaters*. The determining factor for this geographic delineation was the *integrity of each unit in terms of encompassing the major causes and effects of environmental problems associated with each transboundary water area, whether river basin, groundwater, lake or sea. In many cases, a drainage area and associated marine basin (often a large marine ecosystem, LME) were the most appropriate units.*
The World Conservation Union (IUCN), National Oceanic and Atmospheric Administration (NOAA), and other organizations that assist developing countries in implementing ecosystem-based strategies use Large Marine Ecosystem (LME) as the principal assessment and management units for coastal ocean resources. Documentation: Sherman and Duda (1999); http://www.iucn.org/; http://www.noaa.gov/.	LMEs include multiple coastal habitats as they *are regions of ocean space encompassing coastal areas from river basins and estuaries to the seaward boundary of continental shelves and the outer margins of the major current systems. They are relatively large regions...characterized by distinct bathymetry, hydrography, productivity, and tropically dependent populations.*

of sentinel systems ultimately requires investigation of ecosystem functioning and susceptibility to stressors, both of which require further analysis that cannot be derived solely by analysis using geographic delineations. We considered a range of definitions, but began with the definition of coastal areas as less than 100 km inland and less than 100 m in elevation (used by Small & Nicholls, [2003] for coastal population mapping), and with a seaward boundary coinciding with the seaward edge of the EEZ. This delineation encompasses the majority of definitions of coastal areas described in Table 1 and serves as a baseline. Moreover, it is used by the coastal program of GOOS (UNESCO, 2003b) and other planned products for C-GTOS (FAO, 2005). Thus, elevation and distance from coast are two geographic parameters important for defining the coastal ecosystems identified in Table 1, and represent an initial step towards determining key geomorphologic characteristics of potential sites.

Application of the sentinel system framework to identify networks and sites

A coastal observing system must build upon existing initiatives, many of which share sites. They often have complementary, but different, monitoring activities and reasons for site selection. Some networks and programs to draw from include the International Long-term Ecological Research (ILTER), Man and the Biosphere, The Nature Conservancy, the Ramsar Convention on Wetlands and the World Heritage Convention. Many of these initiatives have goals in common with the use of the sentinel system framework for coastal observing system

site selection, both in the process of selection of sites and ongoing support of networks. For example, the US Long-Term Ecological Research Program (LTER) has a strategy to develop long-term and large spatial scale research (Kaiser, 2001; Hobbie et al., 2003). Similar frameworks have also been developed for the ILTER, the International counterpart of LTER, to identify appropriate research questions for regional ecosystem investigations (Christian & Gosz, 2001; Rivera-Monroy et al., 2004). The framework developed by Rivera-Monroy et al. (2004) uses the environmental signature hypothesis to develop a series of research questions for the reef-seagrass-wetland seascape of the Caribbean region. Like the sentinel ecosystem framework, geophysical processes and biogeochemical properties of a small number of different sites will be used to investigate how stressors limit the function of representative ecosystems. TEAM (Tropical Ecology, Assessment and Monitoring) is another initiative compatible with the sentinel system framework. TEAM, led by Conservation International, will support a network of field stations in tropical areas to monitor long-term trends in biodiversity, providing an early warning system on biodiversity change. The selection of TEAM sites will build on existing Conservation International activities, identifying tropical biodiversity hotspots and important wilderness area requiring monitoring (For more information on TEAM, see http://www.teaminitiative.org).

Difficulties are confronted when selecting sentinel sites that were initiated through other programs for a number of reasons. These sites may not have been selected as representative of a particular ecosystems or geographic location. Often sites were selected for pragmatic reasons; sites may have been of local importance, unique in some way, or just more (or less) accessible. Jassby (1998), therefore, states that the problem of selecting sentinel systems is not so much where to put sites, but rather how to analyze better existing sites to serve the needs of the resource assessment. In the context of C-GTOS, this requires the identification of sites that best represent the underlying mechanisms of response to global, large-scale and/or ubiquitous environmental drivers (FAO, 2005). Access and continuity of long-term observations are also key factors to identifying sites that can sustain the types of measurements required. Nations and international bodies with vested interests may then be asked to contribute to the observing system by focusing attention on a limited number of these key sites that can realistically be supported for long-term and coordinated observations. Ultimately the success of the observing system will reflect countries' commitment to supporting these initiatives.

Methods

We identified potential coastal sentinel sites from existing international programs. Sites were also examined to investigate the applicability of various coastal area delineations for coastal site selection. A number of steps were required to achieve this, described in the following sections.

Definition and delineation of coasts

Geographic Information System (GIS) data files were created for the various global coastal areas used throughout the study. These were generated using two data sources: the UN Cartographic Section (UNCS) country boundaries map of the world (1:1,000,000 scale), and the United States Geological Survey (USGS) Digital Elevation Model (GTOPO30) which has a resolution of 30 arc seconds. All coastal area maps were developed by the Environment and Natural Resources Service (SDRN) of the Food and Agriculture Organization (FAO) for the coastal population product of C-GTOS (FAO, 2005). These were based on datasets originally prepared for the Global Poverty Mapping Project of SDRN. A baseline coastal area delineation was developed including all land areas globally less than 100 km inland and 100 m in elevation. Four other global delineations were created, each with an increasing area of land, or buffer, from the ocean-land boundary (5 km, 10 km, 50 km, and 100 km).

Selection of coastal program sites using the sentinel system framework

Site locations and associated data were collected for programs that have monitoring or protected area sites. Data files of site locations were obtained for each organization where available, including publicly available GIS files, online databases, and publications and reports. All available geo-referenced site data were incorporated into a GIS, and the number of coastal sites was then determined for each program or initiatives using the coastal delineations created. Where geo-referenced data were not available, the number of coastal sites was calculated from information published in other sources, based on the program's classification of coastal sites or environments.

All coastal area delineations were used in further analysis of the suitability of various coastal definitions for selecting coastal sentinel ecosystem sites. To achieve this, the number of sites for some of the programs was recalculated using all delineations, and the resulting number of sites falling within these areas was compared. In addition, site data registered in TEMS (Terrestrial Ecosystem Monitoring Sites) was further analyzed. TEMS is the online database of GTOS and contains site metadata information (Tschirley et al., 2003), including information on which sites monitor variables applicable to the four ''phenomena of interest'', or focus issues, identified for C-GTOS (FAO, 2005):

- Human dimension, land cover/land use and critical habitat alteration (37 variables).
- Sediment loss and delivery (22 variables).
- Water cycle and water quality (27 variables).
- Effects of sea level, storms and flooding (13 variables).

We analyzed the TEMS data to determine whether one or more variables relevant to C-GTOS are monitored at each of the sites found within each of the coastal delineations (FAO, 2005). If a site did contain at least one variable of importance to a particular C-GTOS focus issue, the site was considered in the total count of potential sites relevant to that issue. Therefore, the number of potential sites identified within each coastal delineation could be compared for each of the focus issues.

Results

Definition and delineation of coasts

A GIS project was created that contained all of the geo-referenced sites examined and all coastal area delineations developed. Figure 1 represents an example image from the complete GIS showing the location of Ramsar Convention on Wetlands sites and coastal areas delineations for areas less than 100 m in elevation, and 50 km and 100 km from the coast. Although difficult to identify coastal areas less than 100 m in elevation at the scale depicted in the Fig. 1, this does highlight the expanse of coastline where coastal lowlands (areas of low elevation) do not extend very far inland towards the 100 km boundary. The exceptions to this are delta areas, such as the Nile Delta shown in Fig. 1.

Selection of coastal program sites using the sentinel system framework

Each of the 10 programs and initiatives investigated have some proportion of sites or records of monitoring activities in coastal areas (Table 2). Three of the 10 programs have sites recognized as areas of conservation or cultural significance with varying requirements for ongoing monitoring, they are: Ramsar Convention on Wetlands (Ramsar), United Nations Educational, Scientific and Cultural Organization's Man and the Biosphere (UNESCO-MAB), and UNESCO's World Heritage Convention (UNESCO-WH). The remaining seven initiatives have coastal sites or activities that primarily monitor environmental change (Table 2). With the exception of the IUCN (World Conservation Union) Red List, which reports species distribution, all initiatives have fixed site locations varying from a few meters to 1000's of hectares in size, and are therefore suitable for consideration as sources of sentinel sites.

GIS data files with the location of sites for Ramsar, UNESCO-MAB, and UNESCO-WH

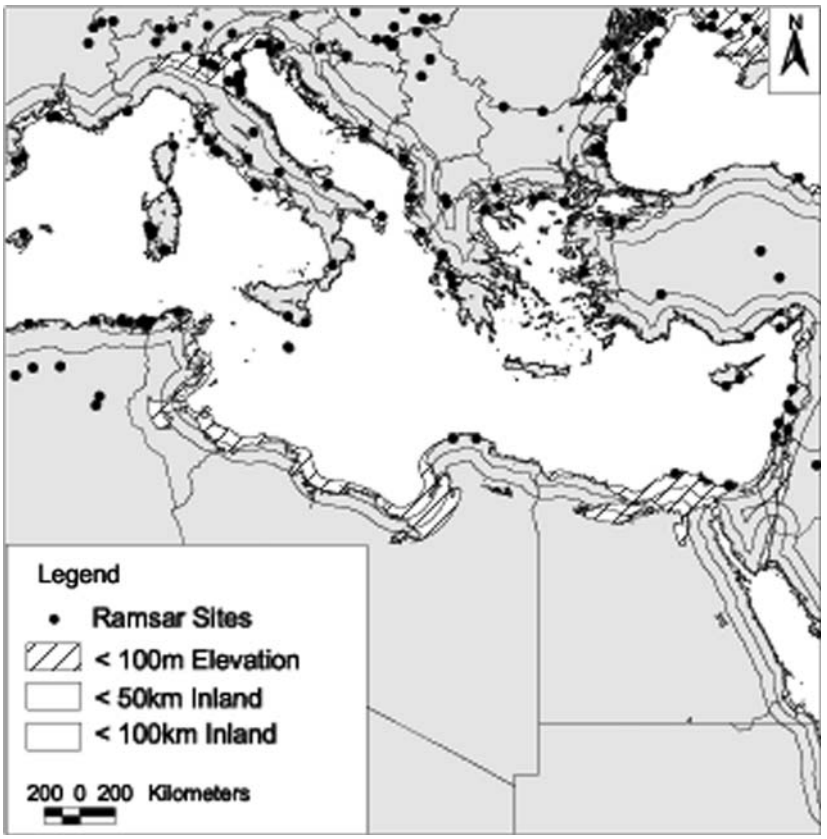

Fig. 1 A GIS map showing project created showing various coastal area delineations and the location of sites of the Ramsar Convention on Wetlands in countries bordering the Mediterranean

were provided by the UN Environment Programme's World Conservation Monitoring Centre (UNEP–WCMC), available as part of the World Database of Protected Areas (WDPA, 2005). GIS data files or information used for the other seven initiatives investigated were obtained directly from the programs and all sources are indicated in Table 2. The locations of sites of the three initiatives for areas of conservation and cultural importance, as well as all TEMS sites, were further analyzed to compare the results of using various coastal area delineations to identify coastal sites (Table 3). The baseline coastal area delineation of within 100 km and less than 100 m in elevation includes between 22 and 29% of the total number of sites for each program, except for Ramsar in which 56% of its sites are coastal. Using a somewhat broader definition, each program has slightly less than half of their sites within 100 km of the coast, with the exception of Ramsar, which has 66% of sites within the 100 km coastal zone. In fact, proportionally Ramsar has more sites proximal to the coast, with at least two times the proportion of sites within 5 km of the coast when compared to other programs. The majority of these Ramsar sites are in low lying areas which can be seen in the small difference of 137 sites (representing less than 10% difference) identified with the baseline delineation (combined distance and elevation) compared to the 100 km distance delineation alone (Table 3). The coastal proximity and low elevation of Ramsar sites can be inferred from Fig. 1, but is more apparent in the analysis shown in Table 3. The trends for the two UNESCO programs (MAB and WH) are very similar, whereas TEMS generally has the least proportion of coastal sites by most delineations (Table 3).

Further analysis of TEMS site data shows that at least 1 variable is measured at each site from one or more of those listed as relevant to the focus issues of C-GTOS (FAO, 2005). Therefore, each of the 2,168 sites examined has relevance to C-GTOS, but not all sites contain variables

Table 2 Existing global initiatives that have observations or sites within coastal areas, as defined by the baseline coastal area delineation

Organization, website, and source of data used	Number of sites or records of monitoring activities, requirements, and frequency	Coastal sites (% of total sites)
Monitoring sites or activities		
GTOS - Terrestrial Ecosystem Monitoring Sites (TEMS) (http://www.fao.org/gtos/tems/; Christian, 2003b)	2168 sites were examined from the total of 2667[a] registered TEMS sites. All sites are must include monitoring at least every 5 years.	482 (22%)
International Organization of Biological Field Stations (http://www.obfs.org)	290+ sites. No requirement for sites to carry out regular monitoring.	[b]
IUCN Red List (http://www.redlist.org/)	In 2004 Red list 4998 species were identified as critically endangered, endangered, or vulnerable. The Red list is updated annually.	154 (3%)[c]
International Long Term Ecological Research (ILTER) (http://www.ilternet.edu/; Hobbie et al., 2003)	The 251 sites registered in TEMS were examined. ILTER sites exist in 25+ countries.	249 (99%)
Land-Ocean Interactions in the Coastal Zone (LOICZ) (http://www.loicz.org/; Smith et al., 2003)	137 individual sites were included from the dataset examined. There is no requirement for regular monitoring.	135 (99%)
ReefBase (http://www.reefbase.org/)	2608 monitoring sites, all of which are reef sites.	2608 (100%)
World Register of Field Sites (http://www.rgs.org/)	377 sites. No requirement for on going monitoring. The register lists field sites and indicates availability of facilities.	17 (5%)
Sites of conservation and cultural value		
Ramsar (http://www.ramsar.org/)	1384[d] sites. Many sites contain ongoing monitoring activities, but no formal requirement.	770 (56%)
UNESCO—Man and the Biosphere Programme (http://www.unesco.org/mab/)	448[d] sites. Many sites contain ongoing monitoring activities, but no formal requirement.	106 (24%)
UNESCO—World Heritage Convention (http://whc.unesco.org/)	801[d] sites. All sites have some reporting requirements. Many sites contain ongoing monitoring activities, but no formal requirement.	231 (29%)

[a] All sites were excluded that did not have the necessary coordinate or network information for further analysis

[b] Information on site locations was not available to determine the percentage of coastal sites

[c] Information on site locations was not available for GIS analysis. The number of coastal sites was calculated using the available database criteria classifying coastal habitats where the data was collected. Data identified as coastal or sea (excluding open oceans) was used. This figure is more representative of the number of coastal endangered species than sampling effort in coastal areas

[d] Number of sites based on analysis of spatial data publicly available for 2005. The number of sites at the time of submission was: Ramsar (1524), Man and the Biosphere (482), Word Heritage Convention (812). Current official numbers are published in the listed websites

important to all four focus issues (Table 4). The variables for the focus issue ''Human dimensions and critical habitat change'' are measured at the most sites across all delineations. ''Sediment loss and delivery'' is the next most observed, followed by ''Water cycle and water quality.''

Only sites within 5 km of the coast were examined for investigation of the focus issue ''Effects of sea level, storms and flooding''. Even though sites further inland monitor relevant variables, the information required for this particular C-GTOS focus issue is for the major part localized to near coastlines (e.g. wind speed). Therefore sites more than 5 km inland were excluded and the resulting 291 sites for this focus issue deal with only the coastal specific variables.

Discussion

Definition and delineation of coasts

Inclusive, yet flexible, definitions of coastal areas for C-GTOS must address user needs, and aid in

Table 3 Number of global program sites located within various coastal area delineations. Percentage of total number of program sites is indicated in parenthesis (%)

Coastal area delineation	TEMS	Ramsar	UNESCO-MAB	UNESCO-WH
Within 5 km of the coast	310 (14%)	592 (43%)	98 (22%)	169 (21%)
Within 10 km of the coast	394 (18%)	670 (48%)	121 (27%)	210 (26%)
Within 50 km of the coast	698 (32%)	861 (62%)	177 (40%)	333 (42%)
Within 100 km of the coast	951 (44%)	907 (66%)	197 (44%)	388 (48%)
Less than 100 m in elevation	519 (24%)	803 (58%)	113 (25%)	246 (31%)
Within 100 km of the coast and less than 100 m elevation	482 (22%)	770 (56%)	106 (24%)	231 (29%)
Total number of program sites	2168[a] (100%)	1384 (100%)	448 (100%)	801 (100%)

[a] All sites were excluded that did not have the necessary coordinate information or network information for further analysis. TEMS has a total 2667 registered sites

Table 4 Number of TEMS sites that monitor variables of importance to C-GTOS, located within various coastal area delineations. The number of sites monitoring variables relevant to each of the four focal issues of C-GTOS is included for each of the coastal delineation investigated

Coastal area delineation	Total C-GTOS related TEMS sites	Sites addressing C-GTOS focal issues			
		Human dimensions and critical habitat change	Sediment loss and delivery	Water cycle and water quality	Effects of sea level, storms and flooding[a]
Within 5 km of the coast	310	263	198	198	291
Within 10 km of the coast	394	333	250	242	–
Within 50 km of the coast	698	607	492	374	–
Within 100 km of the coast	951	838	682	499	–
Less than 100 m in elevation	519	455	358	261	–
Within 100 km of the coast and less than 100 m elevation	482	420	327	250	–
Total sites	2168[b]	1957	1536	1152	–

[a] All sites further than 5 km from the coast were not included in the analysis of sites monitoring the effects of sea level, storms and flooding

[b] All sites were excluded that did not have the necessary coordinate information or network information for further analysis. TEMS has a total 2667 registered sites

site selection. We identified the coastal observations addressed by various programs, and determined the number and location of sites in their networks. A broad spatial definition (from the outer edge of the EEZ to 100 km inland) with an elevation component (less than 100 m in height) was used as a baseline. It allowed identification of a reasonable number of potential ''coastal'' sites (Tables 3 and 4). This delineation encapsulated the majority of definitions of coastal areas used by potential users and information providers to an integrated coastal observing system (Table 1), and is the same as used by the coastal module of GOOS (UNESCO, 2003b). It reflects the reasoning that sites close to the coast but high in elevation are less likely to be influenced by coastal/marine processes than sites in lower elevations. However, some aspects of ecosystems in higher elevations may influence coastal processes. For example, run off from these sites may be important to coastal conditions near these sites. The number of coastal sites defined by 100 km alone was always higher than by the dual factor definition. There was a comparatively small change in the number of Ramsar sites, regardless of if elevation was included as a factor or not (Table 3). Ramsar wetland sites are thus often coastal and found in low lying and near sea areas,

while the mandate of other programs covers broader habitats that may not be aquatic.

Selection of coastal program sites using the sentinel system framework

The identification of potential sentinel ecosystems for a coastal observing network was initiated in steps, each with specific assumptions and constraints. First, we identified programs and initiatives with mandates to monitor environmental change (Table 1). Relevant and long-term data were found to be accessible at a large number of sites within these programs (as was identified in Table 4, examining TEMS registered site information and C-GTOS focus issues). Second, we then developed delineations representing widely accepted definitions of coastal areas and used this to identify a subset of potential ''coastal'' sites from these programs for further investigation. This was found to be crucial step in site selection, as many networks had greatly varying objectives not necessarily coinciding with the needs of C-GTOS; in fact, most initiatives examined had the majority of their sites outside of coastal areas (Table 2). Using this methodology, we focused on 10 specific networks. This approach also proved useful in the interrogation of registered site data in the TEMS database to identify potential coastal sites from other programs and networks (Table 4). Further investigation of registered networks in TEMS will be useful in the selection of sentinel sites, particularly for identification of sites from essential networks such as ILTER. Such networks use TEMS for publication of site, contact, and variable information (for more information see the ILTER website http://www.ilternet.edu/ or TEMS http://www.fao.org/gtos/tems/).

The next steps of selecting sentinel sites will involve closer inspection of the individual sites, direct identification of sentinels among the potential coastal sites, and formal incorporation into a sentinel network. This process will be informed and driven by the joint efforts of the various programs and initiatives, a number of which have been contacted to begin this process, including LOICZ, UNESCO-WH, UNESCO-MAB, and UNEP-WCMC.

Joint efforts between programs using sentinel systems

All networks of sites examined are potential partners in GTOS. The objectives of site monitoring and the networks to which they belong vary widely, but have three broad classes of predominant function, useful in considering collaborative efforts:

- programs with sites of recognized conservation and cultural value;
- programs with sites for monitoring change;
- programs carrying out global and regional assessments of change.

Some collaborative efforts have been initiated within and, to a lesser extent, between these different types of initiatives for some time. Further efforts focused specifically on coastal issues are needed. The following briefly details some of the current status and opportunities regarding this, and identifies how the sentinel system approach may support these actions.

Efforts have been made, through a number of different initiatives to strengthen links between the three programs of conservation and cultural sites examined (Ramsar, UNESCO-MAB, and UNESCO-WH). The most substantial of these initiatives is the mapping of all program site locations through a single geo-referenced World Protected Areas Database, led by UNEP-WCMC. Some efforts have also been made to identify sites in common between the three programs. Eighteen sites where found to be in common between all three programs, 101 sites are jointly MAB and Ramsar, and 75 are in both UNESCO-MAB and UNESCO-WH (for more information see the lists of sites identified on the MAB website: http://www.unesco.org/mab/wnbr.htm). Of these sites, many fall within those identified as coastal in this study and may serve as a good starting point for identification of specific sentinel ecosystems.

Regional and global initiatives that coordinate activities between networks will be instrumental in identifying and synthesizing site data needed for global and regional assessment and observing system programs. This includes initiatives such as GTOS-TEMS, The International Register of

Field Stations (Table 2), and the World Register of Field Sites. Even with such efforts, further collaboration directly between international programs with vested interests in long-term monitoring is necessary for the programs themselves, and for the development of a sustained integrated program of long-term monitoring of coastal change (Kaiser, 2001; Hobbie et al., 2003; Smith et al., 2003).

Many global initiatives, such as the IUCN Red list, use a combination of data from monitoring activities, modeling, and expert opinion to derive global and regional assessment products (Table 2). Such initiatives are potential users of the proposed global network of coastal observation sites and resulting GTOS products. It is not necessarily the case that data used in assessments are derived repeatedly from the same areas or sites. This being said, ongoing global and regional assessments are also obvious partners in developing a network of sentinel sites for a number of reasons:

- Many assessment initiatives do have subsets of data and ongoing monitoring locations that may be relevant to selected coastal sentinel ecosystems;
- Monitoring activities at sentinel ecosystem sites are designed to contribute to regional and global assessments, and collaborative efforts between programs will aid in prioritize these efforts, and save resources;
- There is a large overlap in the network of experts needed for each, at both country and regional levels.

The global assessment initiatives that should be considered include the following (for more information see Table 1 and listed web references below):

- the Millennium Assessment and subsequent regional assessments;
- IUCN Red List, and its partner organizations such as the World Fish Center and FAO that contribute coastal data through programs such as FishBase and the FAO Species Identification and Data Program;
- UNEP activities such as the Global Marine Assessment, Global Environmental Outlook and Global International Waters Assessment;
- coastal and marine assessments of non profit organizations such as World Resources Institute (http://marine.wri.org/projects.cfm), The Nature Conservancy (http://nature.org/) and Conservation International (http://www.conservation.org).

UNEP-WCMC has a marine program active since 2000, and has produced global and regional coastal mapping and assessments products including atlases of mangroves, seagrasses, and coral reefs. At the time of publication, WCMC were in the final stages of completing a Caribbean regional initiative, collecting fisheries data in relation to marine protected areas (E. McManus, UNEP-WCMC, pers. comms.). Activities such as these are key to the development of a coastal sentinel ecosystem network; they bring together assessment activities, monitoring data, and sites of conservation and cultural importance in the coastal zone.

Sentinel ecosystems as a strategy for global and regional observing systems

The Sentinel ecosystem strategy benefits many of the short- and long-term goals of observation programs and national custodians responsible for supporting the day to day activities and on-going management of sites. This approach has several advantages. First and most obvious is that the sentinel ecosystems are directly useful for long-term observations of the particular location and representative for assessment of a broader group of ecosystems. For example, a variety of wetland types have been identified and protected through the Ramsar Convention on Wetlands, and the monitoring of many is integrated into the site management plan. The monitoring efforts vary in intensity, and sentinel ecosystems might be chosen from the most active sites. Monitoring can be promoted in others by leveraging the needs of both Ramsar and GTOS.

Second, implementation of the strategy also builds capacity for providing sustained and quality-assured information for the development,

validation, and evaluation of large-scale modeling and comparative change studies (Rastetter et al., 2003). Simple models of water and salt balance, biochemical stoichiometry, and nutrient exchange have been constructed through Land-Ocean Interactions in the Coastal Zone (LOICZ) at over 200 sites (Smith et al., 2003). A limited number of these sites may also be characterized by much more sophisticated hydrodynamic, ecological process and/or water quality models. These sites may act to validate and improve the simpler models. Modeling efforts can then be transferred to support regionalized modeling efforts advocated in advanced global coastal change programs (Church, 2001).

Third, the strategy links networks with interests in sustained monitoring and conservation of heritage areas. Our approach is to choose potential sentinel ecosystems from these existing networks.

Thus, the application of a sentinel ecosystem framework will be of benefit throughout the development of an in situ coastal observation network; from the process of site selection, to the management of individual sites and coordination of the operable network. Once site selection is complete and stakeholder commitment reached, many of the activities begin that ensure a sustained operational network, including: gap analysis and establishment of required sites; securing of long-term financial and logistical support; development of standards and harmonization of data, inter-calibration exercises, and guidelines for reporting and management. C-GTOS is now taking the next steps in sentinel ecosystem site selection, identifying specific sites, contacting appropriate authorities, and beginning the process of organizing activities among stakeholders supporting sites of long-term coastal monitoring.

Concluding remarks

We have assessed user-based definitions of the coast and used them to develop delineations for the identification of potential sites for coastal observing systems. Sites within international networks represent potential sentinel ecosystem sites. The sentinel ecosystems framework is a strategy for the development of a sustainable network of sites for global observing system needs; the approach will support the development of early warning systems for broad regional and global change, and selected individual sites can form a backbone for comprehensive observations and study. Sentinel ecosystems have relevance to the development and coordination of coastal observation efforts, and in particular to C-GTOS—addressing the observing system's goals of detecting, assessing, and predicting change in coastal terrestrial, wetland and freshwater ecosystems (FAO, 2005). This strategy not only addresses the goals of observation programs, but perhaps most importantly, the needs of countries and national custodians inevitably responsible for supporting the day to day activities and on-going management of sites.

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